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Ramiro Velázquez *Editors*

Mobility of Visually Impaired People

Fundamentals and ICT Assistive Technologies

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About the Editors

Edwige Pissaloux is Full Professor at the University of Rouen, Physics Department, and closely collaborates with the ISIR (Institute for Intelligent Systems and Robotics) at Paris-Sorbonne University and the MIT (France-MIT program). She has authored more than 250 journals and conferences papers. Professor Pissaloux main research interests are the modeling and design of vision systems, cognitive perception systems, and cognitive mobility systems.

Her research has been supported by European funds (EU FP7 Research and Innovation Funding Program), national funds (CNRS, CEA), and international projects (France-UK-Mexico). Professor Pissaloux is a member of several international advisory boards of universities and research institutes, and teaches in several universities (Australia, Hong-Kong, Canada). She frequently acts as an international expert for several research bodies and international institutions such as the European Commission, NSF/USA, Canada, UK, Australia, China, Switzerland, etc.

Professor Pissaloux initiated a series of national conferences such as "Space and its perception: application to design of assistive technologies" or "Eye, gaze and interaction". She has participated and/or co-animated European Excellence networks.

In her free time, Prof. Pissaloux teaches violin for visually impaired children.

Ramiro Velázquez is Full Professor at the Faculty of Engineering of Universidad Panamericana (Aguascalientes, Mexico). He is past Dean of the Faculty of Engineering and currently serves as Vice-President for Research and member of the Board of Governors of this university.

He obtained the Ph.D. in Robotics from UPMC-Paris 6 Sorbonne University in 2006. He has authored more than 100 journals and conferences papers. Professor Velázquez main research interests are assistive technologies, haptic and tactile devices, mechatronic systems, and human–computer interaction. His research projects in assistive devices for visually impaired and blind people have been featured in IEEE Spectrum, CNN, and BBC Horizons.

Professor Velázquez frequently serves as an expert evaluator for the European Commission, CONACYT (Mexico), and COLCIENCIAS (Colombia). He is a member of the Mexican National Systems of Researchers (SNI-Level I).

Introduction

From the Antiquity to the Age of Light, men regard disability as the expression of a divine will, sometimes positive and protective, often harmful and responsible for making men atone for their sins. It was not until the end of the Middle Ages, with the emergence of medicine in Europe, that a more scientific approach to man and its body occurred. However, impaired people remain nowadays assimilated to the broad group of the indigent who experience exclusion from society, often confined in hospitals and asylums. Only recently, social progresses (and their associated legal framework) grant people considered as impaired (with the former name: handicapped people) the right to work, to attend school, to access the information available to others, to participate and to be considered as full citizens.

However, several breaks prevent the real implementation of these social and legal progresses. The access to work, information, the socio-urban structures, and more general to the space are examples of few, still very strong limitations. In the case of visually impaired people the access to the space is a fundamental problem. How to grab a cup of coffee? How to move in the main hall of an unknown administrative building? How to reach a pharmacy nearby? How to perceive the social sign expressed by the state of a face? How to get on a train?

This book attempts to provide some answers to the above questions and others; more generally, the scientific questions which underlie the problems of human–space interactions for impaired human beings. Throughout the book, the elements that answer questions such as: what is the space? how does our brain learn, become aware and master the space in order to allow us to be mobile? what is mobility? how do the visually impaired practically face the space? how does technology provide the support for space perception? for mobility? what should be the most appropriate (thus future) concepts and technologies for true independent and autonomous mobility? will be provided.

The proposed approach is an holistic one, which encompasses, so far, two considered models of disability: medical and social. Indeed, the book aims to provide the unchangeable/immutable bases for the design of new mobility assistive ICT (information and communication technologies) devices for the visually impaired (blind, seniors, firefighters, people whose sight is involved in other complex tasks, etc.), but also for our (humanoid) robots and "intelligent systems".

The holistic framework for mobility is the concept of mobility we have learnt unconsciously in our childhood, which should be rediscovered or discovered as the new technology take us to new spaces (cyber, virtual reality, and stars).

The holistic approach to the design of new (mobility assistive ICT) technology results from exchanges we had during the international workshops on NoE (network of excellence) such as EUCOG (for the Advances of Cognitive Systems, Interaction and Robotics) or CVHI (Conferences on Assistive Technologies for Vision and Hearing Impairments), both supported by the European Commission and, national events (co-)organized in France by the CNRS/GDR STIC-Santé, by the IFRATH (Institut Fédératif de Recherche sur les Aides Techniques pour Personnes Handicapées) and by the PRIMOH (Pôle de Recherche et d'Innovation en MObilité et Handicap).

This book also results from the patience and continuous support of Springer Editorial staff: Zoe Kennedy and James Mary. We would like to thank them for their enthusiasm and advice during the long gestation of this book.

We hope that this book will allow a better understanding of human mobility for healthy and visually impaired people, and the interactions with the space. We hope that the research and practical elements (provided by the mobility instructors in this book) will contribute to new research tracks, to obtain the complete model of human mobility, to generate new mobility paradigms which govern our interaction with the space, to design and implement new mobility curricula for a better social integration of the visually impaired. Furthermore, we hope that this book will be a basis for the design of new academic curricula and research projects dedicated to the design and realization of new efficient mobility aids, which effectively and efficiently assist the visually impaired.

Finally, we take the opportunity to thank all the contributing authors who did a great job.

We dedicate this work to our families.

Who May Benefit from Reading This Book?

The book is designed to inform a wide range of current and future professionals in all domains considered by the book:

Researchers in philosophy, neurosciences, engineering sciences, and locomotion sciences will find several useful and pertinent elements for their knowledge openings to complex domains which may help them for a deeper understanding of their own domains; the book provides the current state-of-the-art in these domains.

To students, the book proposes a scientifically grounded insight into new domains: sciences of mobility and sciences of visually impaired people. Indeed, the book provides examples of technological solutions for the design of new interaction modes and interactive devices, not only for mobility. The outlined solution may stimulate their imagination for designing new innovative technology of high social impact.

For university academics, the book may be an inspiration for adaptation of existing biomedical engineering curricula with a conceptual approach (based on a philosophical framework) to society developments and needs: the book may be a base for such curricula building and even used as a textbook. The locomotion classes offered today only in specific institutions should be transformed in regular classes on space perception. Indeed, several space sicknesses exist: they have been discovered through recent clinical progresses on the sense of balance and with the development of virtual reality technologies. These sicknesses are today rehabilitated with invasive technologies (such as FES, Functional Stimulation System for hemi-spatial neglects, or with TDU, Tongue Device Unit developed by Bach-y-Rita's team for example). The time is to offer noninvasive technologies which reinforces all human capabilities ("augment the man") by the reinforcement of natural sensor-motor perception cognitive loops; such new class of assistive device will adapt the technologies to human needs allowing visually impaired to concentrate on its task (and not on understanding the data provided by the device which is usually the case of existing assistive devices, which require the human adaptation to the technology).

To future technology designers, the book explains which are the philosophical concepts, computational models, and sensor-motor perception cognitive loops that should be investigated in order to design new systems for interaction (for both impaired and healthy people).

To foundations and public organizations (such as the European Commission or FIRAH in France, National Science Foundation, the National Institutes of Health), the book will show the most promising approaches in order to deeper the existing scientific knowledge and new research tracks worthy to explore.

To institutions working with the visually impaired, the book offers a worldwide tribune to establish and exchange the knowledge taught and elaborated by them. Mobility learning approaches and the newest technology are presented. We hope that the book will initiate the dialogue between these professionals and scientific engineers and researchers, and lead to new practices for mobility teaching. Indeed, the new technology will be advantageous with mobility teachers but will never replace them.

For visually impaired associations (AFB in the USA, RNIB in UK, AVH in France, ONCE in Spain, and Blind Associations over the world), the book will provide the latest findings in assistive technologies for mobility and give them an opportunity to evaluate new solutions and contribute to knowledge of the mobility. We hope that the book will stimulate the dialogue and the involvement of the target population in participative design the technologies for them.

An Overview of the Book

The book is organized in four parts, followed by a short note on "Future trends". They are

- Part I, "Space for Mobility and Its Conscious Perception",
- Part II, "Neuro-cognitive Basis of Space Perception for Mobility",
- Part III, "Mobility of the Visually Impaired",
- Part IV, "ICT Technologies and Mobility".

Each part contains several independent chapters.

Part I, "Space for Mobility and Its Conscious Perception", includes three chapters.

Chapter "Living in Space. A Phenomenological Account" by Gunnar Declerck and Charles Lenay highlights the main phenomenological features of lived space. A lived space is the space experienced by the subject through various intentional modes, perceptual or not, frequently based on memory. An overview of the most important phenomenological accounts made in the literature is recalled, with a focus on the following topics: the relationships between motricity and lived space; the relationships between body materiality and experience of space; the role of the anticipation of possibilities in the enacting and organization of lived space; the role of sociality and the impact of one's body 'visibility'. The objective of this overview in the context of this book is to get a better understanding of the experience of space in visually impaired people. Based on this phenomenological account, this chapter will, as a result, offer a series of reflections about the peculiarities of the space blind people live in.

Chapter "Technologies to Access Space Without Vision. Some Empirical Facts and Guiding Theoretical Principles" by Charles Lenay and Gunnar Declerck identifies principles on which the prosthetic perceptual devices works, the conditions of their appropriation, and the general perspectives they open concerning the role of technical objects and systems in the constitution of human experience. As technical device for assisting perception are supposed to compensate a sensory deficit by mobilizing other subsisting sensory modalities, it is necessary to understand the relationship between perceptual activity and sensory input. Finally, the technical devices which assist perceptual activity can in turn serve as tools for experimental scientific research on the mechanisms of perception in general. This chapter investigates these complementary and synergetic approaches.

Chapter "Mobility Technologies for Visually Impaired People Through the Prism of Classic Theories of Perception" by Marion Chotin proposes a return on the theories of the perception of the Classical Age (seventeenth–eighteenth centuries) and asks if these theories are likely to illuminate contemporary techniques of mobility for the visually impaired. The inquiry begins with the Cartesian theory of perception and establishes that Descartes conceived the cane of the blind as an instrument allowing access to new perceptions, under the assumption that a perceptive learning eliminates the divine laws of the union of the soul and the body.

Thus, the Cartesian theory makes it possible to account for the functioning of more recent devices, such as the TVSS of Bach-y-Rita. On the other hand, the Cartesian theory of perception does not describe how one learns how to use the cane. Therefore, the chapter mobilizes the Condillac theory of perception, which, for its part, endeavors to describe how a blind man learns to perceive objects by means of his cane, namely by gradually exteriorizing his sensations. Finally, Condillac's theory is confronted with that of Merleau-Ponty, more frequently mobilized by researchers today, with the aim of evaluating their theoretical and practical contributions.

Part II, "Neuro-cognitive Basis of Space Perception for Mobility", includes four chapters.

Chapter "The Multisensory Blind Brain", by Vanessa Harrar, Sébrina Aubin, Daniel-Robert Chebat, Ron Kupers, and Maurice Ptito, addresses the topic of brain multisensory plasticity and of brain reorganization across the usual sensory boundaries. Through different experiences, this chapter evidences that instead of being sensory specific, cortical regions of brain appear to be functionally specific. Such findings allow the redefinition of current rehabilitation schemes and can be used to improve assistive technologies built for the blind people (as the occipital cortex seems to be amodal).

Chapter "On Spatial Cognition and Mobility Strategies", by Edwige Pissaloux and Ramiro Velázquez, discusses the current state of the art of sensory data which seems to be involved in space perception emergence, in movement perception and in the spatial navigation concept. It outlines also some neural evidences of spatial cognition and some findings on spatial cognition in animals. Finally it recalls some of the most popular models for spatial knowledge structuring and identifies some open questions of spatial knowledge of VIP (visually impaired people).

Chapter "Sensory Substitution and the Neural Correlates of Navigation in Blindness", by Daniel-Robert Chebat, Vanessa Harrar, Ron Kupers, Shachar Maidenbaum, Amir Amedi, and Maurice Ptito, presents the most recent advances in the theory of SS (sensory substitution) and evidences the neural correlates of navigation in CB (congenital blind) people. The analysis of recent theories on the phenomenological properties of sensory substitution and of recent literature on spatial abilities of participants using SS devices (SSD)s show that the sensory information is treated in brain in an amodal fashion. Such results allow CB individuals to navigate in real and virtual environments however and even perform better in a variety of sensory and cognitive tasks. Therefore, the relevant training with appropriate devices may exploit brain's plasticity and create perception and other sensation such as qualia.

Chapter "Visuo-Vestibular and Somesthetic Contribution to Spatial Navigation in Children and Adults", by Irini Giannopulu, discusses all known human parameters involved in the development of spatial navigation skills and their neural correlates. The current state of the art of the influence of multimodal visuomotor, vestibular, and somesthetic abilities for ego motion acquisition and performance, in conjunction with attention and memory processes in real and virtual environments is surveyed.

Part III, “Mobility of the Visually Impaired”, includes five chapters.

Chapter “Orientation and Mobility Training to People with Visual Impairments”, by Mira Goldschmidt, presents the specific mobility challenges of people with visual impairment as well as the strategies and techniques used to improve their orientation and mobility. The chapter also describes the use of mobility devices helping persons with visual impairment to travel safely.

Chapter “Spatial Orientation in Children: A Tyflological Approach”, by Krystyna Nawrocka-Łabus, addresses the concept of spatial orientation and its shaping in children, gives some methodological topics on the work with visually impaired children when teaching them how to acquire the spatial cognition, and proposes some open questions of spatial knowledge of visually impaired people (VIP). This chapter discusses several simple exercises which may be assisted by mobility aids and several games for spatial knowledge acquisition (which may become serious game); moreover, it suggests that the tactile space of children and adult may be different, and touch stimulation representation of the space may require different approaches for adults and children.

Chapter “Scene Representation for Mobility of the Visually Impaired”, by Guillaume Tatur, presents different representations of space proposed in sensory substitution, sensory supplementation, and visual neuroprostheses technical solutions in order to assist the mobility of visually impaired people. The chapter provides also some general recommendations related to scene representation design and discuss the benefits of providing specialized information dedicated to mobility as opposed to a general-purpose representation.

Chapter “Model of Cognitive Mobility for Visually Impaired and its Experimental Validation”, by Edwige Pissaloux and Ramiro Velázquez, contributes to the emergence of the theoretical framework for the design of mobility aids for visually impaired people (VIP). This framework is based on the understanding and interaction (through a touch stimulating device, the underlying sensory motor loops) with space through our senses and proposes a new model of mobility. The chapter briefly discusses different theories for emergence of space understanding from our senses, and recalls some models of human mobility before proposing a new holistic four-component new model of human cognitive mobility. The latter is based on the concept of tactile gist, which reinforces the emergence of sensorimotor loops from our perceptions, for understanding of the organization of a physical space. Some reported original experiments related to the execution of basis mobility tasks confirm the relevance of the tactile gist to represent a space. These latter can be used as a benchmark for evaluations and comparisons of mobility devices, and as a revealer of potential improvements of mobility aids.

Chapter “Solid: A Model to Analyse the Accessibility of Transport Systems for Visually Impaired People”, by Gérard Uzan and Peter Wagstaff, proposes a new model developed to analyze the basic requirements and tasks involved to ensure that optimum solutions to guarantee accessibility to public spaces for all types of user in any situation. The model, developed originally for applications for the blind and visually impaired persons (VIPs) in public transport, is generalized here and can be applied to analyze accessibility in many other situations. In the context of transportation systems, it enables to identify the essential tasks, requirements, and information needed at each stage of the chain of displacements. SOLID is an acronym for the initial letters of the five essential elements of the model, which are Safety, Orientation, Localization, Information and Displacement.

Part IV, "ICT Technologies and Mobility", includes nine chapters.

Chapter "Mobility Technologies for Blind, Partially Sighted and Deafblind People: Design Issues", by M.A Hersh, presents an overview of the most popular travail aids for assistance of mobility of visually impaired. The overview shows clearly the importance of the active involvement of blind, partially sighted and deafblind end-users in the design process of a new assistance; we talk about the participative design. An understanding of how blind people travel, including the ways they use information from all their senses and travel aids, is indeed an essential prerequisite for good design. The chapter provides also a brief presentation of the different phases in the development of travel aides, a summary of the different ways of categorizing them and some principles of good practice for developing new travel aids. Specific features, such as the sensors and interface and features, including privacy management and contextual features, are also considered.

Chapter "Co-designing together with Persons with Visual Impairments", by Charlotte Magnusson, Per-Olof Hedvall, and Héctor Caltenco, proposes a general background on the design process, and follows it by a discussion of human-centered design and co-design. Six concrete examples of design activities illustrate how useful it can be to engage in co-design, and as practical inspiration for future design activities. The examples are followed by a discussion of activities and materials, inclusive design and accessibility and the importance of the context of use. The chapter shows that there is no need to feel daunted by organizing design activities together with persons with visual impairments.

Chapter "Different Approaches to Aiding Blind Persons in Mobility and Navigation in the "Naviton" and "Sound of Vision" Projects", by P. Strumillo, M. Bujacz, P. Baranski, P. Skulimowski, P. Korbel, M. Owczarek, K. Tomalczyk, A. Moldoveanu, and R. Unnthorsson, summarizes several years of research efforts aimed at building ICT (Information and Communications Technologies) based systems for helping the blind in travel and navigation at the Lodz University of Technology, mainly as part of the "Naviton" project. The following prototype solutions are outlined: (1) sonified stereovision system for obstacle avoidance and environment imaging, (2) radio beacons for local navigation, (3) remote assistance system, (4) mobile navigation applications, (5) real-time tracking of public transport vehicles, (6) haptic imaging. These technologies are shortly presented and feedback from end-users, after their evaluation, is reported. The ongoing European project of the Horizon 2020 framework program and entitled "Sound of Vision: natural sense of vision through acoustics and haptics" is also presented.

Chapter "Overview of Smart White Canes: Connected Smart Cane from Front End to Back End", by Gianmario Motta, Tianyi Ma, Kaixu Liu, Edwige Pissaloux, Muhammad Yusro, Kalamullah Ramli, Jean Connier, Philippe Vaslin, Jian-jin Li, Christophe de Vaulx, Hongling Shi, Xunxing Diao, and Kun-Mean Hou, presents the state-of-the-art of ETAs (Electronic Travel Aids) and focuses on their functionalities, hardware architectures and integration of ICT (Information and Communication Technologies) such as cloud computing, IoT (Internet of Things) and smartphone. Connected Multi-Input Multi-Output ETA—called MIMO eETA—will improve safety of the blind by providing more relevant environment perception. Therefore, MIMO eETA will significantly improve VIPs' well-being by easing their mobility and quality of life. Four sections of this chapter introduce (1) general knowledge about VIPs, their mobility, and a classification of electronic devices used to help them in their mobility; (2) a description of a new concept of such tool, the eETA, with the description of its desired functionalities; (3) the current state of the implementation of an eETA, its architecture and related experimentations and (4) the back-end tier is analyzed (its specifications, functions and implementation).

Chapter "Accessible Interactive Maps for Visually Impaired Users", by Julie Ducasse, Anke M. Brock, and Christophe Jouffrais, introduces a novel concept, interactive map for space understanding by visually impaired; its originality comes from the interactivity offered to users which helps them in their understanding of the space geometry, of space geography and in the acquisition of new spatial knowledge. A classification of interactive accessible maps is proposed with two main subclasses: digital interactive maps and hybrid interactive maps. All of them are analyzed and compared. Ongoing and future research in interactive tactile graphics is shortly discussed as well.

Chapter "Smart Multisensor Strategies for Indoor Localization", by Bruno Andò, Salvatore Baglio, Cristian O. Lombardo, and Vincenzo Marletta, focuses on indoor localization implemented by traditional and advanced enabling technologies, measurement strategies, and applications. In particular, the discussion is oriented to perform a benchmark between different solutions with a specific focus in the framework of Active and Assisted Living. A case of study of an Assistive Systems supporting blind people during the exploitation of indoor environments is also presented.

Chapter "Constructing Tactile Languages for Situational Awareness Assistance of Visually Impaired People", by Ramiro Velázquez and Edwige Pissaloux, reports on the findings from an experiment on human performance in tactile language learning and tactile memory. A set of four vibrotactile patterns representing verbal words was presented to a group of 20 voluntary subjects. Upon learning, subjects were capable of recognizing the patterns with high accuracy. Patterns were then combined with the aim of constructing sentences that gradually represent more complex ideas. Recognition rates remained satisfactory for sentences involving two, three, and four tactile words. A novel approach of tactile stimuli was explored: podotactile stimulation. For this study, a prototype of wearable electronic tactile display that stimulates the foot sole with vibrations was used. Results obtained suggest that it is possible to construct tactile languages that could enhance situational awareness feedback provided by assistive devices.

Chapter “Vision Restoration with Implants”, by Akos Kusnyerik, Miklos Resch, Huba J. Kiss and Janos Nemeth, overviews a prosthetic vision solutions, i.e. implants with different operating principles and in various stages of progress. They are presented in detail, with the characteristics of the development highlighted. The continuous evolvement of microelectronics and engineering achieved the development of devices becoming highly similar to the light-sensitive retinal structures. Such an intra-retinal implantable device replaces the photoreceptors and generates biological signals induced by the incoming light. The aim of this chapter is to introduce the reader these techniques and field, and to compare the simultaneous developments of technical novelties and clinical studies.

Chapter “Mobility, Inclusion and Exclusion”, by M.A. Hersh, discusses several topics related to the relationships between visual impairments and society. The importance of mobility for participation in society is discussed first through the accessibility of public transports and private cars. Then, the societal attitudes to blindness are investigated; stigma and stereotypes, acceptance and confidence stigma and use of mobility technology are considered. Finally, the accessible environments are analyzed and some of the potential solutions are discussed.

Part I

Space for Mobility and Its Conscious Perception

Living in Space. A Phenomenological Account

Gunnar Declerck and Charles Lenay

1 Introduction

Accounts of space, its nature and how one's mind can access it through perception or thinking, abound in the history of Philosophy, but broadly two opposite views can be distinguished: realist and constructivist accounts. While realism treats space as an intrinsic feature of the reality with which the perceiving agent must deal, constructivism sees space as an original achievement of the mind, something the mind builds to organize its understanding of reality. The one who opened the way to constructivist approaches to space is undoubtedly Immanuel Kant. Kant rejects the traditional realist view of space, and considers instead space as an a priori form of outer intuition, i.e. what could be described, in more modern terms, as a representation format that is used when processing sensory data. One must make use of this format for the sensory data (e.g. visual or haptic data) to be related to objects *outside* of us, i.e. to acquire what contemporary philosophers of mind call a representational content, present the world as being such and such.[1] For Kant, space is

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[1] As Allais [1: 384] explains, for Kant "it is a condition of the possibility of being perceptually presented with empirical particulars that we represent the world spatially […]." More precisely, "Kant claims that the representation of space is necessary: to represent things as distinct from and outside me; to represent things as in different places/as spatially located; to represent things as spatially related; and to represent things as distinct/different from each other. […] Having, through sensory affection, a presentation of a particular involves representing a thing that is outside of me, is distinct from other things, is located, and is spatially related to other things." [1: 410].

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a property of the objects that are spontaneously presented to one's mind when being sensory stimulated, that is, a property of the *phenomena*, not a property of the mind-independent world that is—putatively—the cause of these stimulations. *Why* our mind makes use of spatial representations is not Kant's concern, but a possible answer (which can be found in neo-Kantian such as Friedrich Nietzsche, Jean Piaget, and Henri Poincaré) is that this representation format has an important practical—and adaptive—value: it enables the subject to find its way in the world in a safe and efficient manner, keep track of targets or remember where things are.[2]

Our aim in this chapter is not to discuss Kantian approaches to space, nor will we defend a Kantian account in the strict sense. Our concern will be to address the experience of space from a theoretical perspective having its roots in Kant, namely *phenomenology*. The objective of phenomenology is not to explain why things are the way they are (identify some conditions C_x to which a phenomenon φ can be causally or ontologically reduced[3]), but it is to describe how things spontaneously appear to our subjectivity, that is, to analyze from a first person perspective the phenomena of consciousness, and generally as they occur in ordinary life. As Heidegger puts it, the task of phenomenology is to describe our being in the world "as it is primarily and usually—in its average everydayness" [60: 37, 38 [17]]. Accordingly, our primary objective in this chapter will be to analyze from a first person perspective the content of our pre-scientific (or naïve) experience of space and the intentional mechanisms subtending this experience. We will consequently leave aside the theoretical understanding of space (its nature and properties) that can be achieved based on scientific modes of explanation and inquiry. Note, though, that we will occasionally mention some empirical data, especially from psychology, generally to corroborate the phenomenological descriptions with behavioural elements. And we will also draw on the way we *speak* of space in everyday language to complement the standard phenomenological approach. We follow J.L. Austin's assumption that the analysis of the way we talk ordinarily, what terms we use to say

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[2] The attentive reader will certainly have noticed that all these formulae are circular: to describe the advantage of representing the—not 'yet' spatial in the strict sense—reality as a spatial world, one cannot do without using spatial concepts.

[3] The canonical form of the scientific explanation is the reduction: to explain an observable phenomenon φ (say, the type of feeling experienced when hungry) amounts to identify a set of conditions C_x, generally belonging to a different ontological domain (e.g. physicochemical or neural informational processes), upon which the apparition of φ is contingent. As a result, φ is considered explained because causally, or even ontologically reducible to C_x (that is, we have $C_x \rightarrow \varphi$ and $\neg\, C_x \rightarrow \neg\, \varphi$); in the latter case, it will be claimed that φ is *nothing but* C_x, which means adopting a form of ontological reductionism. See Searle [102], chap. 5, especially 112–113. "The basic intuition that underlies the concept of reductionism seems to be the idea that certain things might be shown to be *nothing but* certain other sorts of things." [102: 112].

what (what Austin calls the "what we would say when"), carries information about the way we perceive or conceive our world.[4]

Phenomenology is a broad philosophical field, where many accounts of space have been proposed, with sometimes deep disagreements between authors. Our analysis will mainly focus on the following topics: the relation between bodily skills, and more generally motricity (i.e. the capacity to move), and lived space; the impact of one's body materiality on one's experience of space: how possessing a physical body with material properties such as impenetrability and heaviness affect one's experience of space; the role the anticipation of possibilities plays in the enacting and organization of lived space; and, finally, the role of sociality and the impact of one's body 'visibility', i.e. the fact that one can be seen (or more generally perceived) by others, in one's experience of space. An objective behind the selection of these topics is to get a better understanding of the experience of space in visually impaired people. Based on this phenomenological overview, we will, as a result, offer a series of reflections about the peculiarities of the space blind people live in (Sect. 6).[5]

Note, before proceeding, that, from a phenomenological standpoint, lived space can be accessed through different types of intentional (i.e. mental) acts. Two broad categories of intentional acts can be distinguished, *presentational* and *representational* acts.

Perception belongs to the first category. Perception provides a somewhat direct access to space: one directly sees how objects are arranged or one directly hears where sounds come from. In more technical terms, perception is a *presentational* mode of awareness: being perceptually aware of something implies that there is something currently present, something there, that one is aware of.[6]

But space is also something we access though various *representational* modes of awareness, such as memory and imagination. When I engage in an explicit imagery activity about some place I am acquainted with, e.g. think about the spatial

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[4] "When we examine what we should say when, what words we should use in what situations, we are looking […] not merely at words (or 'meanings', whatever they may be) but also at the realities we use the words to talk about: we are using a sharpened awareness of words to sharpen our perception of, though not as the final arbiter of, the phenomena." [5: 182] This is why Austin calls his method 'linguistic phenomenology'.

[5] Note that when speaking of 'space' in this chapter, we generally refer to the continuum that is coextensive with the objective world (which should not be confused with what is sometimes called the physical reality: objectivity, here, is considered in a Kantian sense, as something that is somehow public, i.e. applies for a community of subjects, but which is *relative to* these subjects). Space is that in which we are with our body and where any concrete being must be located to exist (see Sect. 2.3). 'Space' is, in this regard, another term for 'world': this is the world –this world extending ever further, endlessly—considered in abstraction from all it 'contains' and to the extent that it can contain everything. As a result, we will sometimes make use of the term 'world-space', which can be found in Husserl and Heidegger.

[6] As Crane and French [26] explain: "Perceptual experience, in its character, involves the presentation (as) of ordinary mind-independent objects to a subject, and such objects are experienced as *present* or *there* such that the character of experience is immediately responsive to the character of its objects."

arrangement of the shelves of the supermarket where I shop, the space that is made ‘present’ through this mental episode is precisely *not present*, i.e. is not there now (that is, in my immediate proximity). Certainly, the supermarket currently exists, and when I am imagining its spatial arrangement, this is an existing object that I am intending (I can, on the other hand, imagine the spatial arrangement of non-existing or no more existing places, such as the Ancient Library of Alexandria, based on a series of engravings). Though the supermarket is too far to be seen, I know I just have to walk to access it perceptually and ‘be there’. Its ‘presence’ is somewhat founded on its perceptual accessibility [87, 89]. But the arrangement of the shelves I imagine is not there before me now, and the aspects under which I imagine the place are not imposed by my present body orientation, nor immediately responsive to my movements, as it is the case when I perceive it visually. Perceptual presentation makes the object actually there ‘in person’, while non-presentational (i.e. representational) modes of awareness intend their object without making it present (i.e. ‘there’) in the strict sense.[7]

Note that there is another sense in which space is ‘represented’, that applies both to presentational and representational modes of awareness, namely the fact that any awareness of a place implies some—more or less explicit—belief about, or acquaintance with, the spatial characteristics of that place, how it is organized, what you can find in that place and where, or where that place is with respect to some other places, how one can reach it. This points to the everyday sense of the term ‘representation’: how one *figures* (i.e. presumes or reckons or imagines) that something *is*, what features one attributes to this something. How one *conceives* a place undoubtedly plays a decisive role in how one *perceives* a place, that is, in the so-called ‘representational’[8] content of one’s perceptual experience: *what* one sees

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[7] “The object stands in perception as there in the flesh, it stands, to speak still more precisely, as actually present, as self-given there in the current now. In phantasy, the object does not stand there as in the flesh, actual, currently present. It indeed does stand before our eyes, but not as something currently given now; it may be possible to be thought of as now, or as simultaneous with the current now, but this now is a thought one, and is not that now which pertains to presence in the flesh, perceptual presence. The phantasized is merely ‘represented’ (*vorgestellt*), it merely places before us (*stellt vor*) or presents (*stellt dar*), but it ‘does not give itself’ as itself, actual and now.” [68: §4, 12].

[8] As Peacocke [92] explains, “the representational content of a perceptual experience has to be given by a proposition, or set of propositions, which specifies the way the experience represents the world to be.” In other terms, a perceptual experience has a representational content insofar as it presents objects, properties, facts, state of affairs, and so on, that are supposed to be present or be the case in the environment. Note that the concept of representation we use in this chapter has *a purely phenomenological scope*, that is, it aims at describing the content of one’s experience, and should not be taken with an epistemological nor ontological meaning. Especially, this phenomenological concept does not entail a commitment to representationalism, in the classical sense of assuming the existence of neural states that stand in for state of affairs in the external world (see e.g. [24, 31]). The only claim we make is that perceptual awareness, understood as an intentional state, is something that presents the world as being this or that way. Or, to say it a bit differently, in order to describe the perceptual experience of a subject, you need to take into account that this experience presents the world as being this or that way. This is a purely *descriptive* constraint.

(the spatial arrangement one is aware of) when accessing visually to a place depends to a certain degree on what one *already knows* about that place (or the places of this kind). One's prior knowledge about that place *informs* one's perceptual content, first of all by shaping the anticipations or expectations one spontaneously have with respect to one's subsequent experience of that place, what one can see of it, what one will find, if one executes this or that exploratory movement [67: §8 and §25]; [84]. This is what we are going to see with the analysis of a first important feature of lived space, namely its reticular organization.

2 Lived Space as an Interconnected Set (Network) of Places

2.1 The Reticular Organization of Lived Space

A first phenomenological feature of lived space that is worth noting is that it is essentially experienced as a system of interconnected places, which can somehow be equated to a network.[9] Each place is a node that is directly connected to some other places (the neighbouring places) and is only indirectly connected to all the others. Places have a distinct identity (home, office, shop, park, etc.) and are, as it were, compartmentalized (when you get 'into the shop' you are no more 'in the street'), but they communicate in a certain way. Places are parts of a single network, and their situation in this network contributes to define what place they are. Different levels of granularity can also be considered: each dwelling is an autonomous network of places: the kitchen, the living room, the bedrooms, the toilets, the garage, the garden, etc. But it is also a node in the bigger network the city consists in. And the cities are themselves nodes in a bigger network: the district or the country.

How the network is organized depends primarily on how one makes use of it, what places one frequents, and how one gets from one place to another, how much time it needs, and if one must transit through other places. Emphasizing the fundamental reticularity of lived space amounts, in that regard, to putting forward that the structure of space is determined by how one 'operates' in space and navigates one's way across places—thus, as we shall see below (Sect. 3), the essential reciprocity between lived space and one's bodily capacity for action. What places are immediately connected, i.e. constitute adjacent nodes in the network, depends on whether there is an available possibility of transiting 'directly', i.e. without passing by other intermediary places, from one place to another. The cellar and the

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[9] The systematic account of the reticular organization of lived space that we propose in this section is, to a large extent, a personal reconstruction, but one can find elements supporting this view in several phenomenologists, e.g. Husserl [68], Heidegger [60, see especially §22] and Campbell [16].

living room are adjacent nodes, for one can directly reach one from the other: they communicate. But the bedroom upstairs and the cellar are not adjacent, for one must transit through the living room to reach the latter from the former. This reticular organization explains that geographically distant places can be brought closer through modern means of transport. As noted by Erwin Straus, “for the European of the twentieth century, America is much closer than for the sixteenth century navigator. The man whose car was parked at the door of his house is closer to the post office than the pedestrian.” (Straus [107: 455], *our translation*) But this is not only a question of time needed for the travel; what also matters is the number of places one must get through before reaching our destination. Paris Charles de Gaulle airport is ‘directly connected’ to New York John F. Kennedy airport, for one can (almost) directly reach one from the other (the only intermediate place one must get through is the inside of the plane). Both constitute adjacent nodes, and both are ‘close’ in that respect.

It is thus included in our ordinary understanding of space (our ‘concept’ of space) than any place communicates with all the others, in the sense that any place is accessible from any other. Wherever one is, it is possible to access any other place, by passing through the intermediate places. This possibility is a *de jure* possibility, a possibility in principle, not necessarily an actual concrete—a *de facto* —possibility. As a matter of fact, accessing these places may not be possible, e.g. blocked or forbidden, or may require means of transport that do not exist (Pluto’s surface is accessible in principle, step by step, from my living room, but factually it is not).[10] Some places may also have existed in the past but no longer exist today. In this case, they have ceased to be accessible in principle. The part of world-space that these places occupied is now occupied by something else. This is where the train station was located early in the century; today it is a traffic circle.

The reticular organization of lived space shapes the content of one’s perception and is always part of one’s awareness of the situation, first of all one’s implicit knowledge of ‘where one is’. Whatever the situation, one is always, to some degree or another, aware of where one is, one knows what other places one finds nearby, that is, the place where one finds oneself has been assigned a position in the general network of places one is acquainted with. Certainly, it may occasionally happen that one in fact does not know where one is—one may be lost or disoriented–, but when this happens one does not cease to believe that *there are* neighbouring places and that going through these places will finally lead one to a familiar place. Any place adjoins other places: this is a necessary principle. It may seem evident, but the

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[10] Note that the difference between *de jure* and *de facto* possibilities, which is a key element to understand our ordinary experience of space, can be formalized using David Lewis’ and Robert Stalnaker’s possible worlds semantics: a *de facto* possibility is a possibility that can be actualized in the actual world; a *de jure* possibility is either a *de facto* possibility or a possibility that can be actualized in (at least some) other possible worlds. In some possible worlds, means of transport exist that can be used to reach Pluto’s surface. How close (i.e. similar) to the actual world the possible worlds must be for these possibilities to be considered *de jure* possibilities in the actual world is a matter of debate.

pervasiveness of this principle in our spatial cognition is also what explains that in whatever room, you always know (i.e. you live in the implicit certainty) that you can get out.

Our knowledge of (or acquaintance with) the organization of the spatial network also plays a somewhat more direct role in our perceptual experience of places. What one knows about the situation of the place where one finds oneself in the network, what bigger system this place is a part of and what places communicate with it, *informs* one's perceptual experience of that place. It is a fact that the limited portion one sees of a place at a given instant always extends beyond the limits of what strictly speaking one currently 'sees'. What one sees is always seen as *a part* of something bigger.[11] My current visual access to the kitchen is limited to a single part, on which I have in addition a determinate perspective, going with determinate occlusion phenomena. Yet, there are many things (in fact, a whole world) that I do not see but that I expect or know to be there. And the parts that I do not see but extends beyond the portion I see play a pivotal role in determining *the identity* of what I currently see. I identify what I see as 'the kitchen of my house' for I apprehend the part of space falling under my view as having these or those spatial relations with other places, first of all the other rooms of the house, but more generally all the places I know that extend beyond.

A possible description of this phenomenon is that when accessing perceptually to a place, one's perceptual content acquires its spatial content[12] (i.e. it becomes the perception of a given place, accessed from a given orientation) through a 'broadening' process, through which the limited portion of space in view is 'extended' through its inscription in a kind of overall 'map' (see 38: 163, for a similar hypothesis). Before this operation does this job, what one sees is literally *nowhere*, has no spatial connectedness with any other place, and is consequently not oriented. The phenomenon of 'boundary extension' [52, 71], namely the fact that "people remember seeing more of a scene than was present in the physical input, because they extrapolate beyond the borders of the original stimulus" [22: 2068], is an indirect evidence in favour of this claim: it demonstrates that when one sees a place (or a photography of a place), one in fact always perceives more than what one properly 'sees', for one anticipates that there is more beyond. This latter issue points towards a problem known in philosophy of mind as the 'problem of perceptual presence', namely the fact that many aspects of the world that do not currently fall under our perception, are not currently accessed, are nevertheless present, participate in what there is for us now [87, 89].

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[11] As Chadwick et al. [22: 2067] explain: "what we see is always embedded within a wider context. As such, we never perceive what is in front of our eyes in complete isolation, but instead an object is perceived as part of a visual scene, and each scene as one of an infinite set of related scenes that somehow form a continuous sense of space and place."

[12] We consider the spatial content of perceptual experience as a type or subcomponent of its representational content, namely the features of the representational content that are properly spatial.

A final point that must be made is that the reticular organization of lived space is what enables the particular place where one finds oneself to fulfill an exhibiting function (i.e. be the manifestation of) with respect to space considered as a whole. Whatever the place where one stands, this place is part of the general network world-space consists in. Thus, when one perceives a particular place, this is world-space itself that one perceives [68: §59]. We might object that one perceives the room, the amphitheater, the kitchen, not 'space' per se. But these places are not cut off from the rest, they communicate with the adjacent places, and they occupy a specific position in the general network of places: they are themselves 'somewhere'. As Heidegger explains, "the classroom [is] in the university building, the building in the city of Marburg, Marburg in Hessen, in Germany, in Europe, on Earth, in a solar system, in worldspace, in the world." [59: 157–158].

2.2 *What Places Are Is What They Are for*

If places are experienced as nodes in a network, with particular relations of proximity with other places, what primarily defines the identity of a given place (i.e. what type of place it is) is generally an allotted social function. And a social function goes with social practices, which make use of allotted equipment. Heidegger is generally considered the phenomenologist who has systematized this analysis of space [60: §22, 142–143 [109]].

The identity of a place is defined by the kind of things one generally does in that place, i.e. by a "this is where one does this or that" ascription. This is where one sleeps. This is where one cooks. This is where one shops. This is where one takes the train. And the use of each place is subjected to certain social norms, things have to be done a certain way, there are protocols to follow and things that should not be done. How one makes use of space in each place is also prescribed by such norms: stand in line at the store, do not block the passage in the street. In the spatial network, some places distinguish themselves by their merely transitional function: they are places one must go through to reach B from A, but one does nothing in them expect transiting, they are just corridors. Streets are typically that kind of places. Now, the same place can certainly have different functions depending on what people use them, how and when. The main street can be a mere transitory pathway for people going to work in the morning. But it can be a place where one lives and speaks and smokes for teenagers messing around.

Together with their social function, places are defined by the kind of things one expects to find in them, and where, in these places, one expects to find these things: in a kitchen one generally finds a fridge, dry food and tins in cupboards, tables and chairs to sit, kitchenware. Each place presents itself as a system where things have allotted places that depend on what they are for [60: §15 and §22]. Where one finds this or that thing in a given place is prescribed by (and suitable for) the use that is made of that place. Think of a kitchen, of a train station, of the toilets, of the street. And it is not only that the majority of places where one can go, including natural areas (forest, river, mountain, etc.), have been designed by and for human beings; this is how one's immediate understanding of space *works*: wherever one goes one expects things to be 'in their place'.

This system of allotted places is what makes it possible for things to be 'in the wrong place'—which essentially means that one cannot find them where one expects them to be. Note, importantly, that for Heidegger this system of allotted places for equipment is a public fact, accessible for all, this is not a mental representation that would be projected on a meaningless spatial world. How things are arranged spatially depends on what one does with these things, which is related to social norms, not to some private individual facts (on this issue, see especially [81]: 85–86).

To sum-up: places are individuated (i.e. their identity is determined) by (a) their topological situation in the global network and (b) an allotted social function; and (c) the spatial organization peculiar to each place depends on the kind of things one finds in it to do what one is supposed to do in it, the 'equipment' available in this place, considering these things have allotted places that are prescribed by what they are used for.

This analysis of what places are has direct consequences on what it means to experience oneself as *being in* a place. Being in a given place does not only mean occupying this particular position in the network of places, i.e. finding these or those other places in the immediate proximity. Being in a given place (the living room, the kitchen, the street, the park) means to have the equipmental system this place consists of at one's immediate disposal: the places and objects are immediately available for use, they stand 'at hand', as Heidegger says. In the kitchen I can make some coffee, cook something and do the dishes. At the park, I can sit on the bench, enjoy the lake, no longer hear the noise. We will come back to this point in Sect. 4.3 when analyzing the experience of distance.

2.3 Space in the Singular and Space in the Plural

It is important to note that though lived space is fragmented in places, it is nevertheless a whole. Each particular place belongs to world-space, it is a part of it. There is only one space and it is the same for all: space is defined by its uniqueness. In this respect, we must distinguish between world-space (or 'space', in the singular), which is unique, and 'spaces' (i.e. space in the plural), that are many and do not necessarily belong to (or are connected to) world-space in the strict sense. One speaks, for example, of 'green spaces' or 'urban spaces', of 'advertising spaces', of 'political spaces', of 'public spaces' or 'private spaces'; one also speaks of 'digital spaces' and of 'mathematical spaces'. The commercial area, the stadium, the apartment are also 'spaces' in this sense.

What relationship between the two? Given that spaces (in the plural) are of different types, two cases have to be distinguished:

1. Either 'spaces' are parts of 'space' (in the singular) and 'spaces' is then another term for 'places': this is for example the case of green spaces, of the commercial area, of the stadium or the apartment.
2. Or 'spaces' have an abstract nature (in the sense of 'abstract' indicated in the next paragraph) and, in this case, either (a) one can access them through interface devices that are themselves located in 'space' (in the singular); a good illustration is so-called virtual environments, e.g. the space where one moves one's avatar when playing a video game; strictly speaking, the virtual space of *World of Warcraft* is nowhere in world-space, it is not a part of it (that is, it is not a node or systems of nodes that would be *inserted* in the general spatial network); the proof is that you can access this virtual space from (almost) anyplace on earth; however, in order to access this virtual space, you need some hardware equipment that is, like any other material object, located in space; or (b) these 'spaces' are radically abstract in the sense that they have no special relationship with 'space' (in the singular), no point of contact or privileged entry point in it (e.g. a mathematical space, an oneiric space, etc.).

Note that the dichotomy concrete versus abstract as it is traditionally used in philosophy only works if one *already* refers to 'space' (in the singular). Indeed, concreteness is generally defined as the property of that which is located in space and time, i.e. is somewhere and (only) exists over a portion of time (from t_1 to t_2). In this sense, we cannot say that 'space' (in the singular) is concrete, for it would amount to saying that space is located in itself. Conversely, abstractness is generally defined as the property of that which is *not* located in space and time (e.g. 'freedom', 'hate', 'redness'). When we say that *a space* is abstract, it is thus to say that this space is not located in space (in the singular), that is, is not *a part* of it.

The previous remarks show, in addition, why space, in a strict sense, cannot be equated to a concept. While many chairs can be found in the world, so that we can treat these particulars as different instances of a same concept that includes any real and possible chair, there is only one exemplar of space, which is itself. Space is unique. Surely, as previously explained, one speaks of multiple 'spaces'; however, when doing so, this is either to refer to *parts* of 'space' or to something that, in any case, cannot be equated to an instance of 'space', for, in order to be an instance of 'space', it would necessitate that the entity be itself located in 'space', and this is precisely not the case (abstract spaces are, by definition, abstract). Space is, to that extent, much alike an individual and speaking of 'space' is like using a proper noun. Note that this is not true for other notions that are closely related to space, such as the notion of *place*: we can speak of a *concept* of 'place' because there are many places in the world, each particular place exemplifying the abstract concept of place. As a result, 'space' (in the singular) is not something one comes to know through an abstraction process, going from concrete particulars to general abstract features corresponding to the invariants properties shared by these particulars. ‘Space’ is rather known through an explicitation and extrapolation process, going from parts (the particular places one comes to meet) to the whole that encompasses all of them. This whole is, however, not a finite being one could grasp through a bird-eye-view. It is an open-totality: there are always other places beyond the ones one can reach or think of. There is always more.

3 Lived Space As Shaped By One’s Body

The analysis of space as a network of places has already shown that how one ‘operates’ in space and navigates one’s way across places, thus one’s bodily skills, is an essential parameter in one’s awareness of space. Space is experienced as a network of places to the extent that one can *move* from one place to another. But, more radically, the organization of this network reflects some properties of one’s being-in-space-with-a-body, such as the fact that: (*a*) one cannot be here and there at the same time, i.e. one is bound to the position occupied by one’s body; (*b*) one cannot immediately transfer oneself from one place to another (i.e. ‘relocate’), but must move, which takes time and energy, and sometimes money and (*c*) one cannot pass through walls, so that only certain paths can be followed to access one place from another. And of course, the social practices from which the places’ identity derives are rooted in bodily skills: ‘what one does’ in this or that place is, to one degree or another, something one does with one’s body.

The claim that one’s body plays a constitutive role in one’s experience of space is among the chief claims phenomenologists have put forward to account for lived space. The thesis of most phenomenologists is that space as one ordinarily experiences it *is shaped by one’s bodily skills*, i.e. by what one *can do* with one’s body, and that motricity (the ability to move oneself) is a fundamental ingredient of space perception. One experiences space because one can move, and the type of spatial organization one is aware of at each moment is patterned by the nature and range of one’s motor skills. As [38: 157] for instance explains: “the spatial information embodied in […] perception is specifiable only in a vocabulary whose terms derive their meaning partly from being linked with bodily actions.” That is, the critical parameter to address the embodied nature of one’s experience of space is the body as an action organ, i.e. the body as that through which one acts. This claim has been developed in Husserl, especially through the idea of kinesthetic constitution of spatial perception, but it has been given its most systematized form in Merleau-Ponty [82] and subsequent authors having built on his work and belonging to what is sometimes called the embodied or enactive approach to cognition (e.g. [36, 43, 70, 86, 87, 89, 90, 106, 116, 122]).[13]

In the following, we will not only insist on the role of what one can do in the shaping of lived space, we will in addition insist on the role of what one *cannot* do because of one's bodily nature, which is something much less considered in the phenomenological literature. The constitutive role of embodiment in one's experience of space can be addressed at multiple levels. We will examine two: (a) the egocentric mode of manifestation of lived space; (b) the impact of one's body materiality on lived space.

3.1 The Egocentric Mode of Manifestation of Lived Space. Where Things Look to Be Depends on Where One Is

Asking where is an obvious way to cope with space in ordinary language; but 'where' does not have one single meaning. What one means when asking or when telling where something is depends on contextual parameters, such as the kind of object that is considered (where Alpha Centauri is is not defined at the same scale as where the bathroom is, or where the butter is, or where one's mind is), or why (i.e. for what purpose) one wants to know where this something is. Sometimes one wants to know where something is just to talk. Typically, I meet my new colleague John for the first time, and to break ice, I ask him *where he lives*. He could tell me: in the United States or in Germany, or he could answer that he lives in the *quartier de Montmartre* in Paris or even tell the exact address (for a similar distinction, see [19: 118–119]. If one wants to know where something is to access it and use it, the description of its location will be considered acceptable from the moment it provides enough indication to get one's hands on it. I am phoning John with who I must go to a meeting. We said yesterday that we will join somewhere then go to the meeting together (John knows how to reach the university from the centre, I don't). 'Where are you?', John asks me on the phone. What John wants to know when asking this question is where I am *so that we can join*. What he wants is a series of indications that will help him to find me. I could tell him: 'I am just in front of the

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[13] To what logical relation the relation of *constitutive dependence* between embodiment—bodily action or motor skills—and space perception amounts to is an epistemological challenge in itself and is beyond the scope of this chapter. The relation of constitution is, basically, a conditional relation: saying that A is constitutive of B (or that B constitutively depends on A) amounts to saying that B is conditional on A: A must be for B to be (or B cannot be if A is not). But the proponents of the embodied approach seem to intend something stronger than (or differing qualitatively from) a merely causal relation, typically a type of mereological relation. De Jaegher et al. [32] e.g. explain: "P is a constitutive element if P is part of the processes that produce X." This view could however be challenged for one can think of cases where B constitutively depends on A without B being a whole of whom A is a part. One reason is that B can constitutively depend on A even if A and B are of different ontological kinds, while the part of relation seems to apply only to entities of the same ontological kind.

big shoes shop just beside the postoffice and there is also an orange juice seller'. Or: 'I am near a big red building, which looks like a train station'. If I see where he is I could also tell him where I am with merely egocentric indications, e.g.: 'I am approximately fifty meters on your left'. Or, if we both have a GPS, I could tell him: 'I am at Latitude 48.856614 and Longitude 2.352222'.

These ordinary situations illustrate the deeply context-dependent character of the locating process. Locating something (including oneself), i.e. answering the question 'where is X?', always starts by choosing a frame of reference that makes sense in the context in which the question has been raised. Where something is depends on *why* (for what purpose) one wants to know.[14]

Now, the thesis of most phenomenologists is that, *in perception*, such frame of reference is primarily given by one's body. The spatial features one accesses through perception include a (so-called 'indexical') reference to oneself as a centre of reference. Any something that appears to be 'there' is 'there' relative to one's 'here' [66: §41, 166 [158–159]]. In other terms, the reference frame in which objects presented perceptually get spatial coordinates has a fundamentally egocentric character.

Surely, space is also experienced and conceived in an 'objective' and allocentric way.[15] While in an egocentric reference frame the object's location is defined by reference to the subject's own position ('the door over there at ten meters on the left'), in an allocentric reference frame it is defined independently of the subject's position (or positions of parts of her body), by reference to another reference frame (allocentric means firstly non-egocentric). This can be a geocentric reference frame [91]: the Leaning Tower of Pisa is said to lean by reference to the gravity vertical axis; or an object-base (i.e. environmental) reference frame, i.e. a "spatial frame of reference allowing to locate objects with respect to each other" [75: 688]: the bathroom is near the bedroom, the bread is on the table, John is in the garden. In short, allocentric coordinates do not depend on one's own location in space, while egocentric coordinates do [125: 70]. As a result, the characteristic of an allocentric description is that it remains true whatever the location of the subject.

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[14] This feature has especially been stressed by John Locke. "This modification of distance that we call place was made by us for our own use, and we fit it to our convenience. When men speak of the 'place' of a thing, they do it by reference to those adjacent things that best serve their present purpose, ignoring other things that might be better determinants of place for another purpose. When we are playing chess, it wouldn't suit our purpose to locate the pieces in relation to anything except the squares on the board; but quite different standards apply when the chess-men are stored in a bag and someone asks 'Where is the black king?' and the right answer is 'In the captain's cabin'. Another example: when someone asks in what place certain verses are, he doesn't want an answer that names a town or a library or a shelf; he wants an answer such as: 'They are at about the middle of the ninth book of Virgil's Aeneid', which remains true however often the book has been moved." [78, Book II, chap. 13: §9].

[15] Though it is now widespread in the phenomenological literature, the distinction between egocentric and allocentric spatial representations comes from psychology where it foremost refers to the kind of reference frame that is used by an individual to represent the location of an object in space [12, 25, 75].

Allocentric space is, however, the result of a *process of objectification* that builds on egocentric space. Phenomenologists, and especially Husserl, have described the different subjective operations that are involved in this process. Among these operations, the objectification of one's own body seems to play a pivotal role: one must apprehend oneself *as an object* in space among other objects in order to apprehend space as an objective system whose features are not bound to one's current point of view on it. As Zahavi explains: "we only experience space as objective when its coordinates are no longer being experienced as being dependent upon [our] indexical 'here'. But it is only by objectifying the body, only by viewing it as an object among objects, that its indexicality can be surmounted or suspended." [126: 105; see also [38]: 163] Zahavi notes that "this already occurs when one speaks about moving *through* space" (Ibid.). Indeed, considering that one's position in space changes implies to see one's own body as an object. To that extent, in order to understand how one comes to perceive and conceive space as objective, it is necessary to identify what mechanisms make it possible to experience one's own body as an object. Among the key parameters involved in the latter process are the possibility of experiencing one's own body in reflexive touch [26, 65, 79, 80, 82][16] and the possibility of seeing oneself through the eyes of other subjects, that is, adopting an intersubjective perspective on one's body [54, 65, 126].

Conversely, it is worth noting that the 'self-relatedness' that defines the egocentric system of reference cannot be thought of as a reference to the body conceived *as an object* that is itself located in space, in which case this would amount to an allocentric representation [75, pp. 688–689]. As Campbell [16: 74] explains, "when the subject is identifying places egocentrically, it cannot be thought of as doing so by first identifying a physical thing—itself—through a body image, and then identifying places by their relation to its body […] the egocentric identification of places does not depend upon a prior [objectifying] identification of a body". The question is: what is the nature of this body on which the egocentric reference frame is based if this is not *an object* in the strict sense?

Merleau-Ponty is probably the first to propose a systematic account of this question. This account consists, in short, in equating the body to an *action organ*, that is, a system of action possibilities we spontaneously rely on as embodied agents. When I look at an object oriented upside down, e.g. the face of somebody lying down on a bed from behind, what I see looks inverted (i.e. not correctly oriented) because I anticipate that I could see it upright if I had another position. "I feel that I could, if I wanted, walk round the bed, and I seem to see through the eyes of a spectator standing at the foot of the bed." [82: 252] My bodily ability to move there and see the object from a different perspective is what gives sense to what I see from here, it is what the invertedness of the object refers to. The same is true for

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[16] Husserl e.g. explains: "As *perceptively* active, *I experience* (or can experience) *all of Nature, including my own animate organism*, which therefore in the process is reflexively related to itself. That becomes possible because I 'can' perceive one hand 'by means of' the other, an eye by means of a hand, and so forth a procedure in which *the functioning organ must become an Object and the Object a functioning organ*." [65: §44, 97 [128]].

the upright orientation of objects. “Each object has its ‘top’ and its ‘bottom’ which indicate […] its ‘natural’ position, the one which it ‘should’ occupy”, because one’s gaze is used to “[meet] it at a certain angle, and otherwise fails to recognize it.” [82: 252] The ‘normal’ orientation of objects is determined by what Merleau-Ponty calls, following Husserl, one’s optimal *perceptual grip* on it.

Certainly, the vertical orientation of the perceptual field has something to do with the gravity axis, i.e. with the geocentric reference frame. But the vertical gravity is only involved because we have a body that must stand and walk. Gravity determines the orientation of the perceptual field to the extent that it is something we must deal with when going about our activities in the world: to live, we must move, and to move we must stand and keep balance.[17] As a result, Merleau-Ponty emphasizes, “What counts for the orientation of the spectacle is not my body as it in fact is, as a thing in objective space, but as a system of possible actions […]. The possession of a body implies the ability to change levels and to ‘understand’ space, just as the possession of a voice implies the ability to change key.” [82: 249–251] For Merleau-Ponty the same holds for the other basic principles on which perceived space is organized, especially the distance (near-far) dimension [see 82: 254 sqq.].

It is important to see that Merleau-Ponty’s account only partially solves the problem described above. Assuming that the space one perceives is oriented because one apprehends this space as a space *in which one can act*, two major issues must be clarified: (a) what does ‘acting’ mean, here? In particular, does the term exclusively refer to perceptual actions, that is, actions whose purpose is to modify one’s *perceptual relation* with the environment? Or does it also include ‘behavioural performances’ (for this distinction, see Sect. 4.2)? An obvious problem is that one can apparently perceive space as oriented or as organized in depth even in case one cannot *in fact* perform any action in it (the things located in space may be inaccessible or one may be paralysed). This leads to a second difficulty: (b) in what sense of ‘can’ does the spatial organization of the perceptual field refers to what one *can* do? Is it something one can effectively do right now, an immediate practical possibility? Or is it something one can do in principle (or could have done) or something others can do?[18] Merleau-Ponty was, to a certain extent, aware of

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[17] As Charles Taylor explains: “The up-down directionality of my field is a feature which only makes sense in relation to my action. It is a correlative of my capacity to stand and act in equilibrium. Because my field is structured in a way which only makes sense in relation to this capacity, I can say that the world as I perceive it is structured by it; or that I see the world through this capacity. But a field of this structure can only be experienced by an embodied agent.” [110: 24].

[18] We do not develop this complicated issue in the present chapter. But see Declerck [28].

these difficulties,[19] but we can doubt he provided an analysis of the role body skills play in spatial awareness capable of addressing them in an appropriate manner.

Note finally, and this will make the transition to the next point, that the egocentric organization of perceptual space is related to a fact that can be easily overlooked because of its obviousness, namely *that we are ourselves in space* when we perceive it. Space is always experienced *from the inside*: we are in it, and not *before* it and *outside* of it, as when looking at a painted landscape at the museum. This feature is presupposed by the structure of egocentric space: the things we perceive appear to be there *relative to us* and at this distance *from us*, because we are ourselves located in space, i.e. we share the same world. Conversely, we cannot speak of distance for visual objects that do not belong in the same world as us, e.g. objects represented on a painting or seen through a stereoscope. For these objects to be somewhere *with respect to us*, it would require us to be with them on the other side of the painting, in the pictural space, somewhat like Lewis Carroll's Alice.

3.2 Living with a Body in Space. Space as that in Which One Must Find a Place

Another critical sense in which lived space is shaped by one's body is related to its materiality, more precisely its impenetrability to other bodies, the fact that it will oppose resistance if other bodies try to penetrate its substance.

Being somewhere generally[20] implies being somewhere with (or through) one's physical body. This sounds like a truism, but this is a key point many phenomenologists have emphasized when analyzing one's perceptual experience of space: through one's body one has a direct grip on the things around, one can achieve a sensorimotor contact with them and one can make use of them, i.e. exploit their affordances. This is what Dreyfus [35] calls one's skillful everyday coping with things. But—and this is now something phenomenologists, including Husserl, do not generally pay attention to—being somewhere with one's body also means *being subjected to a series of constraints one must deal with*, to have some 'duties' to fulfill. It means first of all being encumbered with a body one must *place somewhere*, i.e. to occupy—literally—some space [27, 29]. To that extent, the key point to understand the embodied character of one's perceptual experience of space is not

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[19] "How can I perceive objects as manipulatable when I can no longer manipulate them? The manipulatable must have ceased to be what I am now manipulating, and become what *one* can manipulate; it must have ceased to be a thing *manipulatable for me* and become a thing *manipulatable in itself*. Correspondingly, my body must be apprehended not only in an experience which is instantaneous, peculiar to itself and complete in itself, but also in some general aspect and in the light of an impersonal being." [82: 82].

[20] This is not always the case, for one can be located in virtual spaces without being there with one's physical body. See below, Sect. 3.3.

only what one *can do* with one's body, it is also, symmetrically, what one *cannot do* because of one's being-a-body.

If one did not have to move, the fact that one takes up space would not cause difficulties. One could simply keep one's place. The problem is that one cannot (and does not want to) stay where one is. One must move to live. One must change one's place. And to change one's place, one must find a place, i.e. one must fit one's body where some room is still available. And this is not an easy task. Most often, the places where one lives are literally saturated with bodies (whether animate or inanimate). Think of the subway or train station at rush hour. Think of a supermarket. Think of your own dwelling. And it is only because one knows how to deal with this cluttering that one can make use of places, do what one generally does in these places using the available equipment (see Sect. 2.2). In the park, before I can make use of this bench to relax, I must access it. To get there, I have to go along the fence, pass the gate, give way to this old man, walk around the tree, avoid pigeons. I cannot reach the bench in a snap and I cannot get there in a straight line. And of course, I run the risk that another body takes the place before me. Any displacement in space is an obstacle course: one must maneuver, work around, push and shove the bodies that bar the way or impede the passage.

Our contention in this chapter is that this day-to-day challenge, namely *finding a place*, exerts a significant pressure on the organization of lived space. The *format* in which space presents itself in perception is imprinted by the (implicit and practical) awareness that one takes up space and must, each time one moves, find a place. The space one perceives is—so to speak—*designed* and, in a sense, optimized, for this inescapable and pressing task.

The most obvious expression of this principle—namely, that lived space is shaped by the awareness of encumbering space with one's body—is one's immediate ability to discriminate between empty space and occupied space, or, more generally, the role this distinction plays in one's understanding of space. Empty spaces, e.g. holes, are obviously an important ingredient of one's naïve ontology, i.e. one's ordinary representations of the kind of entities one finds in the world [17–19]. The hole in the cheese is there, it does not have less existence than the cheese itself. You see this hole, you can put something in it, you can even cut it in half; holes are so real that not having enough holes can be a reason for not buying a cheese in the supermarket.

A fundamental way in which one deals with holes or openings, or more broadly empty spaces, in ordinary life, is by taking them as potential places for one's body or for objects. Empty spaces are spaces where one could put things, where one could be, through which one could pass. (Some empty spaces are also openings through which one could be seen; see Sect. 5.) Emptiness is essentially perceived as the availability of a place. "Even when we talk about 'naked' (empty) regions of space—regions that are not occupied by any macroscopic object and where nothing noticeable seems to be going on—we typically do so because we are planning to move things around, or because we are thinking that certain actions or events did or should take place in certain sites as opposed to others. The sofa should go right here; the aircraft crashed right there." [18: 73].

The ability to perceive empty spaces is among the chief abilities that are exercised in the task of moving oneself in space or, more generally, coping with space. I see that there is enough room to pass. I see that there is a place where I can seat. I see that I can walk through this aperture. Several studies from the ecological psychology literature and the action-specific approach to perception have furnished empirical data supporting this claim [see, e.g. 41, 104, 118, 120]. This is also true for the objects one manipulates. I immediately see the empty space between the dishcloths and the bottles of cleaning products under the kitchen sinks, and I immediately see that there is enough space for storing the bucket. How much space is available for placing objects is immediately visible. I do not have to measure anything. And I do not have to think. One reason is, as Gibson first showed, that the presence of empty spaces such as holes and passages is specified by typical patterns of optical information that the visual system can easily pick up [47, 49].

A possible way to express the shaping relation between the material properties of one's body and perceived space is to make use of the concept of 'effectivity' that was proposed in the ecological psychology theoretical framework to account for what affordances are offered to a given agent by a given environment or object [103, 114].[21] The impenetrability of one's body—the fact that it will oppose resistance to any other body coming into contact with its surface—is part of the effectivities defining the impassability of a region of space (e.g. a wall, a dense vegetation, a compact crowd), its property of not-affording-passage, or what Gibson calls the bump-into-ability of physical structures, i.e. their character of obstacle. Keep in mind, however, that for a region of space to acquire the character of being impassable, one must in addition have the capacity to move (or, at least, to *be* moved), and typically to walk: one's body impenetrability makes a region of space impassable only to the extent that one could try to move through this region. This is in fact a general rule when considering the shaping of lived space by one's body. The properties of one's body determine the organization and phenomenological properties of lived space, which, as a result, somehow 'reflect' the properties of one's body. But these properties shape lived space only to the extent that they shape one's actions, i.e. determine *what* one can do and *how* it can be done.

How people perceive and find their way in crowded places is particularly informative about the relation between, on the one hand, the constraints the material properties of one's body put on one's possibilities of occupying space, and, on the other hand, how space appears to us in perception. When trying to find one's way in the subway at rush hour, or in the station when one has to hurry up not to miss one's train, one tends to perceive the surrounding space as a mere field of obstacles: bodies block the way and must be circumvented, some openings can be passed through, some objects can be moved, others must be walked around. The spatial layout of bodies tends to be exclusively seen from the perspective of practicability.

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[21] "An effectivity of an animal (or human) is *a specific combination of the functions of its tissues and organs taken with reference to an environment*. The notion of effectivity may be schematized as follows: *An animal Z can effect action Y on an environmental situation or event X on occasion O if certain relevant mutual compatibility relations between X and Z obtain*." [103: 197].

People themselves are perceived as mere masses hindering one's progress. The bodies define the limits where one can move and stand, and this is only to that extent that one perceives them: as constraints on one's field of possible displacements.

The passability or impassability of a region of space also depends on socionormative parameters. I have the right to go through a passage or penetrate a —otherwise forbidden—region of space if I am empowered to do so by my administrative function or social status. At the Customs Airport I cannot pass beyond the line. At the pub, I cannot go on the other side of the bar. Basically, I cannot enter private properties; or I cannot enter the intimate space of someone if I am not a relative [56]. Note that the term 'cannot' has, however, a slightly different sense in that case, for impassability does not absolutely exclude the possibility of passage: I can violate the rule of not using the passage. Here, 'cannot' does not mean that I am not able to or that it is impossible to; 'cannot' means that I am not *allowed to*. In addition, socionormative impassability is always a matter of degrees. The space may be more or less impenetrable, depending especially on what one incurs (what risk one takes) if penetrating it. The situation is, however, still more complex for very often the interdiction of penetrating these spaces is embodied by a physical device that makes this penetration *really* impossible: a wall, a barricade, a fence, a counter. Think of the Berlin wall. The merit of this type of device is not only to ensure the respect of norms (transgression becomes impossible), it also enables a certain attention and cognitive sparing. People do not have to constantly check that they respect the norm.

Once again, the notion of affordance is a valuable resource, for we can apply it to social behaviours, that is, we can include social norms (rules) and social statuses (one's own social habilitations) in the set of effectivities deciding of what can or cannot be done with this or that structure, object or place. We generally think of the role of the social dimension in affordance perception merely in terms of 'social affordances', that is, opportunities for social *interactions*: perceiving that this interaction with others is potentialized by the social environment, e.g. that one can answer the smile of that girl, or that one should better not look into the eyes of this angry guy.[22] But social norms not only frame opportunities for interacting with other *persons*, they also determine what can and cannot be done with *objects* (understand: not persons), e.g. whether one can enter a region or touch or grasp something, or how this shall be done. That is, many actions that are not 'social' in the strict sense are patterned by social norms.

Keep in mind that the distinction must, however, be maintained between what *can* be done (depending on one's body properties and abilities) and what *shall* be done (depending on one's social status and social norms). What shall be done is always something that can be done. Conversely, one can choose not to comply with

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[22] This meaning has especially been promoted by Rietveld. "Social affordances are a subcategory of affordances, namely possibilities for social interaction offered by an environment: a friend's sad face invites comforting behaviour, a person waiting for a coffee machine or smiling can afford a conversation, and an extended hand affords a handshake." [98: 208].

what shall be done: social norms can be violated. One can enter a forbidden space. But one cannot enter a space that does not afford penetrability, e.g. a wall.

3.3 When One's Where Is not Determined by the Position of One's Physical Body. Immersion in Virtual Spaces

We have seen in Sect. 3.1 that an essential phenomenological feature of space is that it is always from the inside that one perceives it: one is oneself located in space when one accesses space through perception. This point could be radicalized, by saying that this space within which one is is, in addition, something from which one cannot escape. One cannot get out and one cannot cease to be somewhere. As Eugen Fink explains: "We are born in the world and we depart the world in the world" Fink [39: 230, *our translation*]. And this is, in a sense, another phenomenological feature of lived space: when one perceives space, one has the implicit belief (or conviction) that one is, say, locked in space: one knows that, whatever one does, one cannot leave, and this knowledge also impacts how one perceives space, especially for what regards the feeling of 'presence' (compare with your experience of being-in a virtual space: if something goes wrong in it, you know you can get out).

This being-(locked)-in-space derives in a sense from one's being a body. In a way, one perceives space from the inside *because* one is a body that is itself located in space. But, from the phenomenological perspective, this is not so simple. Especially, this being-in-space-as-a-body should not be considered an objective fact. Remember that phenomenology does not build on objectivist assumptions: you can *see yourself* as an object; but *being* an object (say, a physical system where physiological processes take place) is never taken by phenomenologists as accounting for what one sees and how one sees it. To experience oneself as a body located in space is itself the result of an intentional process, namely the process of objectification that we have mentioned in Sect. 3.1.

As a matter of fact, phenomenologically speaking, being located in space through one's physical body *is not* a necessary condition to be *somewhere*. Most often this is your physical body that sets your location: you are where your body is. Your body is in this amphitheater, sitting on this uncomfortable stool; *you are* in this amphitheater, sitting on this uncomfortable stool. There are, however, many situations when one's physical body is not what determines one's position in space. When controlling a physical or a virtual avatar, say a flying drone or a cursor on the computer screen, this is the avatar that decides of where one is. One is on the screen, moving from a window to another. This is reflected in ordinary language: I am playing a war planes video game with John; we are both slaloming though enemy fires, the screen is a chaos with dozens of enemy planes. 'Where are you?' John tells me. 'I am here, just near the big one'. 'Oh I thought you had stayed behind, I almost shot you'. In these situations, one has ceased to be where one's physical body is, the ‘there’ of the avatar has become one’s here. This is what is generally called immersion.[23]

An immediate reply we can think of is that in these situations, one is not *really there* with the avatar, one is still *here* with one’s body controlling the avatar; claiming that one is there is a kind of metaphorical way of speaking or an abuse of language.

Though this reply undoubtedly makes something right about the kind of fundamental anchoring in space that is achieved by one’s body (in a way or another one is somewhere *because* one has/is a body *and* one is always where one’s physical body is[24]), from a strict phenomenological standpoint this claim is not acceptable. The metaphorical view neglects at least two important facts about the intentional mechanisms that subtend one’s lived spatial location (i.e. ‘where one feels to be’): (i) first, the fact that “my body is wherever there is something to be done” [82: 250], that is, the critical role of practical concern and current activities for defining one’s location; (ii) second, it leads to not seeing that one’s physical body generally sets one’s location *because it itself fulfills certain functional requirements*; in other terms, having the experience of being located where one’s physical body is is itself the result of a subjective process, where critical parameters can be indicated.

This can be understood through the following thought experiment. Sam suffers from classical state locked-in syndrome [9]: he is almost totally paralyzed, the only motor capacity he retains is vertical eye movements and blinking. But he has learned to move a cursor on a screen through a brain-computer interface. The avatar he controls through the device has become his only window on the world: everything he does that has a sense for him happens in or through the virtual space where his avatar moves. Sam can surf the Web, he has a FaceBook page with many friends and a Blog, reads e-books, and through the interface he can also control many things in his room: he has a voice synthesizer he uses to speak with the medical staff or his relatives, and he can control the tilt of his bed. As a result, where Sam is *most of the time*, is inside the virtual space where the avatar is moving, there ‘on the screen’, not in his hospital bed. He ‘gets back’ in his hospital bed when something goes wrong with the interface, when something hurts in his physical body, or when the social environment addresses him as his body, e.g. when the nurse or his relatives ask him, while looking into his eyes, how he feels or what he has ‘done’ today.

A critical parameter for something one controls to become one’s ‘here’ is direct responsiveness to one’s practical intentions [20, 113]. In normal conditions, the

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[23] In the five stages scale proposed by Auvray [8] to analyze the process of immersion, the feeling of being there with the avatar corresponds to the fourth stage (‘Distal localization’). A description in English of the immersion model of Auvray [8] can be found in Auvray et al. [6] and Gapenne [45].

[24] Another argument we could think of is that each time one is immersed in a virtual space, sooner or later, one gets back. Virtual spaces are spaces in which one is immersed only intermittently. This is not a necessary feature, however, for we could imagine virtual spaces from which one never gets out. Science-fiction has often played with this possibility. Think of Christopher Nolan’s *Inception*, for example.

organic body is directly responsive in that specific sense: immediately one's intention to move and do something (grasp this glass, go there, type a sentence on the computer screen, speak that word) embodies in the appropriate action [82: 145–146], there is no delay, not even the experience of 'controlling' something, no separation between what one intends to do and what one does. Thanks to this responsiveness, as Descartes puts it, "I am not merely present in my body as a sailor is in a ship, but […] I am very closely joined to it and, as it were, intermingled with it, so that I and the body form a unit" [33: 56 [81]] Only when there is a loss of responsiveness (e.g. one's arm is paralyzed because one has slept on it) does one come to experience one's body as an organ that does not work anymore, and symmetrically to perceive oneself as *what controls* that reluctant 'thing' that does not respond as it should, a mind locked in a body. But as long as it works, one's body is something one confounds with, something one is, not something one has (i.e. possesses and controls). All this implies that being one's body, and being here where one's body is, is the result of a process of embodiment—a process of identifying oneself to one's body [34]. One becomes one's body because one's body works correctly, because there is a kind of immediacy between one's practical intentions (what one wants and expects to do) and one's movements (what one does).

The responsiveness to intention is not the only variable for body appropriation. The visual location of 'body sensations', i.e. haptic and proprioceptive sensations, is another critical parameter. It is now well-known that one can make someone feel some external thing accessed visually to be 'her body' (i.e. control her feeling of body ownership) provided one generates tactile and proprioceptive sensations that are consistent (i.e. occur in synchrony) with the visual input [2, 14, 37].

Note, finally, that the possibility of experiencing oneself out there with an avatar does not challenge the assumption that in order to be somewhere one must be somewhere *with a body*. In the case of virtual environments, this body will be one's avatar.

4 Lived Space and Possibilities. What is and What Can be

Another pivotal claim that has been defended by phenomenologists is that one's experience of space constitutively involves a form of *anticipation of possibilities*. This is something we have already glimpsed in the previous section: the critical parameter when considering the shaping of lived space by one's body is what one *can* (or cannot) do with this body, i.e. the action possibilities one anticipates or takes for granted when accessing perceptually to the surrounding. Remember Merleau-Ponty's analysis of spatial orientation: the *possibility* (which is for the moment—we must now insist on this—*just* a possibility: it is not realized yet, and nothing ensures that it can in fact be realized) of seeing the—now inverted—face upright if I had another position is what gives sense to its invertedness: the way I see what I see constitutively refers to the possibility of having other perspectives on what I see. But, as we will show, practical possibilities are only one type of possibilities playing a critical role in one's experience of space. What can be *done* is one thing, what can *be* is another. And what one believes one can do is always something one believes to be *possible*: what can be done is a part of what can be.

4.1 To See Space Is to Foresee Possibilities

The claim that one's experience of space is based on (or structured by) an intentional relation to possibilities (the exact nature of this relation is, as we will see, an issue in itself) has been put forward by many authors, the first to systematize this position being probably George Berkeley in his *Essay towards a new theory of vision* (1709), and is nowadays sometimes referred to as the berkeleyian account of space, which many authors have followed since. The most prominent advocates of this position include, by chronological order: Bergson [10], Poincaré [93], Husserl [65, 67, 68], Heidegger [60], Scheler [101], Straus [107], Sartre [100], Merleau-Ponty [82], Evans [38], Taylor [110] and Grush [55]. In the field of psychology, this claim has especially been defended by Gibson [46, 49] in his ecological theory of perception,[25] and by Proffitt [94, 95] in the context of the action-specific (or 'economy of action') approach to perception.

In short, the claim is that being perceptually aware of the spatial properties of something (and, basically, being aware that something is in space, is a spatial entity) cannot be separated from, is conditional upon, amounts to or is reducible to (for authors defending a strong reductionist position), being aware that certain possibilities can be actualized provided certain actualizing conditions are fulfilled.[26] This is because one anticipates what may (or may not) be (done), that one experiences space; one could not experience space if one's perceptual apparatus would just take a photograph of what is the case in the environment at time *t*. Perceiving space implies to foresee (and presupposes a commitment to) what can be the case in the future or, more radically, is conditional upon the apprehension of what could have been the case *now*.

This claim has been defended for various spatial properties, but most of the time this is for egocentric distance perception (sometimes called *depth* perception) that it has been emphasized, with, in addition, a focus on motricity, that is, the ability to

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[25] See e.g. Gibson's analysis of the cliff and locomotion affordance [49: 157–158].

[26] This must be distinguished from the claim, accepted by most psychologists, that the spatial content of one's experience *generally triggers* or *can trigger* (provided additional conditions are fulfilled) beliefs or expectations about possibilities realizable with the spatial object. According to this claim, one can perceive something as a spatial object (i.e. one's perceptual experience can have a spatial content) without making these inferences or having these beliefs. For this approach, the connection between the action possibilities and the experience of space is loose, and action possibilities cannot be said to be truly constitutive of spatial experience.

move, and especially to walk. Locating something one perceives in the distance, assigning a place to an object in perception, implies to refer this object to one's possibilities to access it. The basic prediction of this claim is that provided a given objective distance between one and an object, a change in one's capacities to access the object will result in a change in its phenomenal distance, i.e. how far it seems to be.

Note that this claim, formulated in this way, is only postulating a functional or conditional relation between two intentional abilities, namely the ability to perceive space and the ability to anticipate (generally action) possibilities. Believing that some possibilities are realizable with object O is a condition for experiencing O as a spatial objet; one cannot locate O in space without making these inferences or having these presumptions. But we will see that some authors go further, and assume that to perceive space *is* to be aware of such possibilities: *seeing* that this object is there is *fore-seeing* that this or that can be done or may be the case. This stronger—reductionist—version of the claim thus holds that these inferences about what can be done or may happen are precisely what constitute *the content* of one's experience of something as spatial: locating something in space is nothing else, and nothing more, than to make these inferences. In other terms, the awareness of a given spatial property F is *reducible*, in terms of content, to the awareness that some possibilities are realizable (under appropriate circumstances). For instance, seeing that the chair is at this distance before me *is* to believe that this or that possibility is actualizable with the chair provided this or that condition is fulfilled.

Berkeley's account of visual experience undoubtedly belongs to this second—reductionist—category. The leading claim of Berkeley can be phrased the following way: the visual experience can only acquire a spatial content, i.e. represent the spatial organization of the surrounding world, to the extent that it supports anticipations about the behavioural possibilities directed to the objects being presented visually. Considered in isolation, visual sensations are devoid of spatial content: in particular, they carry no information about the distance of objects [11, §.2]. What provides the visual experience with a spatial content is the mapping of visual sensations with these actions (done many times in the past) that can be executed to approach the objects so as to interact with them (manipulate them, use them). In other terms, the visual content presents objects located in space, because visual sensations work as *signs* (in Berkeley's words) for the actions that can be directed towards these objects, first of all ambulatory behaviours, i.e. moving close to the objects (generally to grasp them, and in any case to make use of them) [11, §.59]. Note that what Berkeley had in mind was the connection between visual sensations and haptic and proprioceptive sensations (though in a broad sense), not with behavioural possibilities in the strict sense. The berkeleyian account retains an empiricist—lockean—approach to perceptual experience (i.e. focused on the notion of sensation). Henri Poincaré holds a very similar view in that regard, which is well summarized by his claim that "to localize an object simply means to represent to oneself the movements that would be necessary to reach it" [93: 47]. What Poincaré refers to here is the rules governing how the sensory input varies when one produces some actions. Poincaré is, as a matter of fact, a precursor of the sensorimotor approaches to perception.

Note finally that Berkeley and Poincaré aside, it is not always clear what version of the claim is held by the phenomenologists defending this somewhat ‘dispositionalist’ approach to space perception.

4.2 What Kind of Action Possibilities One Anticipates When Perceiving Space

A noteworthy issue raised by the dispositionalist approach is related to the *nature* of these possibilities the anticipation of which putatively plays a constitutive role in one’s experience of space. As said above, phenomenologists generally refer to action possibilities, that is, possibilities of doing things with one’s body, typically the possibility of approaching distant objects. But the actions one can perform are varied, and not all have the same function; they can also be considered at different descriptive levels.

The dispositionalist approach has essentially been defended with regard to two types of actions (or two perspectives on the same actions) by phenomenologists: (1) actions causing changes in the sensational content of experience, i.e. *exploratory* (or information-gathering) actions; (2) actions enabling to make use of objects, i.e. *performatory* (or executive) actions.[27] According to the first view, what matters for perceiving space is the anticipation of the changes in sensational content that would result from one’s movements, that is, the functional relation between the sensory data and one’s field of *kinesthetic possibilities*. For the second view, ordinary space is structured by the *possibilities of use* afforded by objects and places, the value of these objects for achieving one’s practical projects, the anticipation of what can be done, how, when, and at what cost. What matters in the first case is what I can *see*

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[27] The distinction between exploratory and performatory actions was initially proposed by Gibson [48, 49] in his description of the haptic system, and has been later clarified by Gibson [50] and Reed [97]. While *exploratory actions* aim to extract information from the environment (e.g. eye-focusing on an object or exploring an object with the hand) and are typically used for the control of activity [97, pp. 80–81], *performatory actions* aim to use or manipulate the environment (i.e. change states of affairs). Performatory actions thus cover the activities that are generally put under the label of *behavior*. Another difference between these two types of actions is that they generally have different energy requirements, “*Exploratory activity*, as I call the scanning for and use of information […] involves the adjustment of the head and sensory organs to the ambient energy fields. These adjustments are typically embodied in cyclic, low-energy and low-impact movements of the sense organs or the head. […] *Performatory activities* are precisely those cases in which the animal does use significant amounts of force to alter the substances and surfaces of its environment. It is one thing to see or to smell a piece of food, it is quite another thing to obtain it, masticate it and eat it–and this applies whether one is a dragonfly or a mammalian carnivore.” [97: 80–81].

(or, more generally, 'sense') if I move; what matters in the second case it is what I can *do,* or better what I can *use*, when.

These two views are not necessarily exclusive. But the fact is that they have generally been defended by different authors holding opposite positions. What mainly distinguish the two approaches is in fact a difference in focus and granularity of analysis. While the authors promoting the first view are mainly interested in the qualitative aspect of phenomena, i.e. the sensational layer and the functional connection between motor acts and sensory changes, the authors favouring the second view generally disregard this layer of phenomena as a theoretical construct that does not reflect the way things really appear to us in ordinary perception, and focus instead on our everyday coping with objects and its social significance (Heidegger is undoubtedly the main representative of this latter view).

Poincaré is a typical example of the first account (see above, Sect. 4.1). So is Husserl. For Husserl, the visual perception of tridimensional objects located in space is not possible without sensations of movements, i.e. what Husserl calls kinesthetic sensations or *kinestheses* [see e.g. Husserl 68: 136]. Rigorously, we should speak of kinesthetic *acts*, for in Husserl the kinestheses are hardly identifiable to sensations as they have traditionally been understood: they rather correspond to the lived experience of motor acts when being executed, and 'before' these acts produce muscle contractions and bodily sensations; they bear, to that extent, an essential relationship to will and to what Husserl calls the 'I can'. For Husserl, the kinestheses are constitutive of one's experience of spatial objects by virtue of the counterfactual structure of perceptual intentionality, its 'if-then' organization.[28] When identifying something in perception, one registers that which one perceives under a given sense (*Sinn*) which enables to anticipate that it will exhibit this or that familiar appearance in case this or that change in the perceptual circumstances occurs, especially in one's kinesthetic situation. This set of expectations is borne by what Husserl calls the 'inner horizon' of objects [67: §8, 32]. The kinestheses motivate systematic changes in the visual data, and they are articulated with the latter into a whole functional system; as a result, to locate something in space in visual perception always means to expect a set of functional connections between the movements of one's body, head and eyes, and changes in the visual appearance of the object. This is especially true for the kinesthetic possibility of moving toward or away from the object. As Dorion Cairns explains: "the visual object is presentationally given in 'far' and 'near' appearances. If it is presented as far, there is indicated a horizonal act in which it would be presented as near. This horizonal act is indicated as a motivational potentiality, to be realized by realizing a certain

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[28] *Thing and Space* is probably the book of Husserl where this approach has been the most developed. See also *Krisis*, §28. Gallagher & Zahavi propose a good summary of Husserl's position on that matter: "The absent profiles are linked to an intentional 'if-then' connection. If I move in this way, then this profile will become visually or tactually accessible. The back of the car which I do not see has the meaning of 'the back of the same car I am currently perceiving' because it can become present through the execution of a quite specific bodily movement on my part." [44: 110].

functionally related sequence of kinaesthesia, the 'loco-motion' kinaesthesia." [15: 153] More radically, for Husserl kinestheses are a *sine qua non* for the sensational content to assume a figurative function, that is, for the perceptual experience to acquire a representational content, presents the world as being this or that way.[29] One's kinesthetic system and the confidence that one can move (the '*I can*') thus play an essential role in the constitution of spatial objects: this is because one is capable of moving and know (or believe or expect) that one can move that one perceives space, tridimensional objects (that is, objects with other sides, now invisible, but visible from other points of space) disposed in a gradient of distance.

Note that most theoretical accounts of perception in enactivist frameworks have adopted and sometimes developed this same idea. One of the contemporary defender of an enactive account of this kind is Alva Noë [87, 89]. The main contention of Noë, which has been systematized through his so-called actionist theory of perception, is that the objects we are aware of through perception (which does not mean—considering visual perception—that we *see* them, in the strict sense: they can be out of view but nevertheless present) are defined by their sensorimotor accessibility. To perceive thus implies to know or believe or anticipate that this or that would occur in one's perceptual experience if this or that movement were produced [see 88: 533]. Though Noë pretends to defend a direct realist theory of perception, assuming in addition a disjunctivist position [see especially 89: 23–24 and 112–113], his position is reminiscent of the husserlian approach, but also of empiricist and 'sense-data' accounts of perception, a position dating back to Berkeley and John Stuart Mill, and developed in the 20th century by Alfred J. Ayer, Bertrand Russell, and George Edward Moore, to cite only the prominent figures.

4.3 *Phenomenal Distance as a Measure of Availability for Use*

The second approach to the role of possibilities in lived space is mostly represented by Bergson,[30] Straus and Heidegger, and focuses on a different layer of phenomena, namely the behavioural possibilities that are made available (i.e. potentialized by)

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[29] For Husserl, this claim applies at least for the visual and haptic presentation of spatial objects (i.e. 'material things'). It is an open question whether this claim should more generally apply to any perceptual modality and any type of objects one can perceive, including e.g. smells and flavours [on this issue, see 53]. One can hardly defend that the exercise of one's ability to move or the anticipation of the sensory changes that would result from our kinesthetic acts play the same critical role in the perception of smells and flavours, than in the visual and haptic perception of spatial objects.

[30] 'Officially', Bergson does not belong to the phenomenological movement, but, at least in his book *Matter and Memory*, he promotes a descriptive approach very close to phenomenology.

or impacted by the environment, i.e. in general terms, what can or cannot be 'done' in it.[31] This analysis of distance consists in subordinating (and maybe equating, the claim is not totally clear) phenomenal distance with availability for use, i.e. in a nutshell with *practical accessibility* (with 'practical' understood in a broad sense, not reducing to motor activity). Generally, realistic assumptions lead theoreticians of space to see practical accessibility as something derived from, and determined by, objective distance: that which is close is within reach because it is close; that which is far is beyond reach because it is far. The—possibly counterintuitive, due to the widespread character of realistic assumptions—contention of phenomenologists is that practical accessibility is what comes first: that which is close is close *because* it is within reach, not the inverse.

This is particularly evident in Bergson. Bergson explicitly equates the distance at which the objects one perceives appear to a measure of their unavailability: the more distant an object is, the less readily available it is, the less one can count on it for achieving one's immediate practical projects. "This very distance represents, above all, the measure in which surrounding bodies are insured, in some sort, against the immediate action of my body. In the degree that my horizon widens, the images which surround me seem to be painted upon a more uniform background and become to me more indifferent. The more I narrow this horizon, the more the objects which it circumscribes space themselves out distinctly according to the greater or less ease with which my body can touch and move them. They send back, then, to my body, as would a mirror, its eventual influence." Bergson [10: 6–7] To see at what distance something stands is to foresee how available or unavailable it is for a possible 'use' or, more generally, interaction (for good or ill). Erwin Straus holds a similar position [see Straus 107: 455–456].

Note that an apparent corollary of this claim is that objects are distant in space because they are distant in time. Something is remote because it cannot be used now; some time is needed to make it available. To perceive the distance of an object —this tree in the distance, the garden table a few meters ahead—is to appreciate how important is the gap between its present unavailability and its future availability, for instance how much walking is needed to get it at hand. Seeing something as being there in the distance amounts, in one word, to anticipate how much time (*how long*) it would take to reach it. Erwin Straus e.g. explains: "The there of remoteness is where I am not yet arrived […]. What I see in the distance, what I

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[31] It is difficult to classify Merleau-Ponty in this second category, for the action possibilities Merleau-Ponty deals with are quite exclusively sensorimotor activities, what he calls the relation of 'grip' one can achieve with the spectacle [see e.g. 82: 261 and 296]. In other terms, the action possibilities Merleau-Ponty describes as playing an essential role for the spatial organization of experience are possibilities of *seeing more or better*, not possibilities of *doing*, i.e. coping with things and exploiting the affordances they make available. This is a striking difference with Bergson or Straus (not to speak of Heidegger): as Cataldi [21: 44] explains, whereas "Straus defined the *remote* as that which is removed from my longing or that which is beyond the reach of my desire", "Merleau-Ponty […] defined *increasing distance* as 'expressing merely that the thing is beginning to slip away from the grip of our gaze'".

perceive as near or far is before me as a goal, more exactly as located in the future." (Straus [107: 456], *our translation*) Two remarks must be made with this claim.

(1) Firstly, this time that apparently decides of spatial distances is not the objective time measured by clocks. The time it takes to access something, upon which the distances are scaled, is itself measured—by a sort of equivalence operation—by the ordinary activities we are familiar with and which take more or less time. If a place 'is about a half-hour walk', our understanding of what represents 'half an hour' is set by the time it takes to do things one can do in 'half an hour'.[32] In addition, other parameters related to activity obviously come into consideration, in particular the difficulty of access and the effort it would take to reach the object. Some empirical studies have clearly highlighted this point: for instance, subjects weighted with a load making their moves more difficult perceive objects as farther away [96, 123].

(2) Secondly, many ordinary situations seem to go against the claim that two objects are at equal (perceived) distance from the moment that accessing each would require an equal amount of time and effort.[33] It would take the same amount of time to access the rocking chair at the other end of the room and the stool, which is nearer in terms of objective distance, but cannot be accessed without walking around the coffee table; and reaching the stool would surely require a bigger effort (at least attentional) than the rocking chair, which can be accessed in a straight line. Yet, visually speaking, the distance to the stool is undoubtedly smaller than to the rocking chair. One can see that 'objectively' the stool is nearer than the rocking chair. Does this conflict with the precedent account of phenomenal distance? Apparently, the only possible way to overcome this issue is to consider that the distance at which things appear visually primarily refers to an *idealized* reaching action. For judging the distance to objects, visual perception ignores to some extent the deviations and detours that would impose an effective displacement to them: perception thinks in straight line, so to say. As a result, the time needed to access the objects is indeed what decides of their distance, but this action has an abstract character: it does as if the path to the objects was always free (but see [85], for qualifying this claim).

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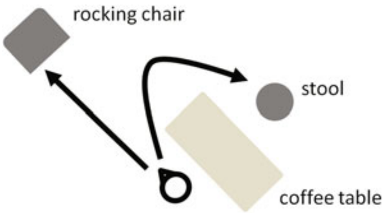
[32] "Remoteness is never understood as measurable distance. […] We say that to go over there is a good walk, a stone's throw, as long it takes to smoke a pipe. These measures express the fact that they not only do not intend to 'measure', but that the estimated remoteness belongs to a being which one approaches in a circumspect, heedful way. But even when we use more exact measures and say 'it takes half an hour to get to the house', this measure must be understood as an estimation. 'Half an hour' is not thirty minutes, but a duration which does not have any 'length' in the sense of a quantitative stretch. This duration is always interpreted in terms of familiar, everyday 'activities'." [60, §23: 98 [106]].

[33] As Straus explains: "The objective distance that separates me from the blotter and the inkwell on my desk is certainly different for these two objects, but their proximity is equal if I can grasp each of them with a single hand movement." (Straus [107: 455], *our translation*).



Heidegger's analysis of phenomenal distance is reminiscent of Bergson's and Straus' views, but it is more developed and also more radical in its claims. In addition, contrary to Bergson and Straus, Heidegger conceives the relation of 'use' with the objects without explicitly referring to bodily skills (Heidegger is well-known for having 'neglected' the body in his phenomenology). The basic point to understand Heidegger's account of distance is his rejection of the objectivist approach, namely the view that perceiving space equates to building a mental representation of an objective space with intrinsic metrics (the space of the physical reality), so that the spatial features one perceives are prescribed and constrained by a fixed preexisting order. This is what Morris [86: 9 sqq.] calls, following Merleau-Ponty, the *ready-made* theory of space. For Heidegger, objective distances cannot decide about the 'nearness' and 'farness' with which things appear in our everyday absorbed coping; at best they are only one parameter in the equation [see e.g. 60: §.21, 90 [97]]. "In the course of a hike through the woods I come for the first time to Freiburg and ask, upon entering the city, 'Which is the shortest way to the cathedral?' This spatial orientation has nothing to do with geometrical orientation as such. The distance to the cathedral is not a quantitative interval; proximity and distance are not a 'how much'; the most convenient and shortest way is also not something quantitative, not merely extension as such." [62: §16, 72] What decides of the nearness or farness of the things one deals with is their availability and accessibility, which are not an affair of objective distance, but depend on what Heidegger calls one's circumspective understanding of things.

This claim cannot be understood in abstraction from Heidegger's analysis of the way things appear to us in our everyday coping with the world—what he calls the 'being-concerned-about' (*Besorgen*). Heidegger uses the term 'availableness' or 'readiness-to-hand' (*Zuhandenheit*) to refer to the mode of being with which things present themselves 'primarily and usually': when absorbed in one's everyday activities, one does not perceive 'objects', one is dealing with equipment (*Zeug*), and what one 'sees' (or foresees) first is *what they are for*, what could be done with them, how they could help achieving one's goals, or, on the contrary, how they could hinder this achievement [61: §.15, 163–164]. In addition, contrary to 'objects', the equipment one deals with in everyday coping is never apprehended in isolation, but "always belongs [to] an equipmental whole, in which it can be this equipment that it is" [60, p. 68]. Any equipment refers to other equipment, e.g. the pen refers to ink, paper, table, furniture, etc. [35: 62]. And this "specific functionality whole is *pre*-understood" before any individual piece of equipment we come to meet [61: §.15, 164]. The heideggerian notion of practical circumspection (*Umsicht*, literally 'for-sight') refers to one's non-thematic acquaintance with this equipmental whole and ability to cope skillfully with the equipment. This kind of 'sight' [60: §15, 65 [69]] is what enables one to anticipate that this or that piece of equipment must be used to achieve this or that action, and to plan action sequences, i.e. to know what must be done with what and when to achieve a given practical purpose (e.g. crossing the street, smoking a cigarette, washing the dishes). It is this kind of 'knowledge' that is behind one's everyday behavioural performances and the apparent ease with which one spontaneously orients oneself in one's practical world.[34]

The core of Heidegger's thesis about phenomenal distance is that practical circumspection is the intentional mode under which the distance of things is primarily experienced in everyday coping. The more immediately something is usable, the nearer it is [60: §22, 95 [102]]. What *matters* given our current practical concerns is thus what decides of the distances. Heidegger uses the concept of 'de-distancing' (*Ent-fernung*)—literally, cancelling the 'farness'—to refer to the intentional process that brings things in the field of view of practical circumspection. When I am about to do the dishes, only a part of the equipmental whole is 'neared' by my practical circumspection: the sink, the dirty items: plates, cutlery, glasses, the sponge, the faucet, the dish soap, the tea towel. These things have their familiar place. And I am directed practically towards them as resources to perform the work. These are those pieces of equipment that are currently nearest to me. As Malpas [81: 76] explains, this 'bringing-close' or 'nearing' "is not just an overcoming of a purely objective *spatial* distance but also a 'picking out' or a 'bringing into salience' that overcomes the distance of inattention or 'not-seeing'." Which does not mean, conversely, that one is explicitly paying attention to them. On the contrary, what has been brought in the field of circumspection is generally only peripherally and implicitly present; one is in a way or another counting on it or with it, but one is not explicitly paying attention to it.

As a result, in Heidegger, 'nearness' is more or less equivalent to 'available for use'. That which is immediately available for use, *at hand*, is what presents itself as near. Conversely, the more something is 'far' from one's current practical concerns, the more 'distant' it is. Heidegger thus explains: "What is supposedly 'nearest' is by no means that which has the smallest distance 'from us.' What is 'near' lies in that which is in the circle of an average reach, grasp, and look. […] For someone who, for example, wears spectacles which are distantially so near to him that they are

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[34] "Circumspection uncovers and understands beings primarily as equipment. When we enter here through the door, we do not apprehend the seats as such, and the same holds for the doorknob. Nevertheless, they are there in this peculiar way: we go by them circumspectly, avoid them circumspectly, stumble against them, and the lie. Stairs, corridors, windows, chair and bench, blackboard, and much more are not given thematically. We say that an equipmental contexture environs us." [61: §.15, 163].

'sitting on his nose,' this useful thing is further away in the surrounding world than the picture on the wall across the room. This useful thing has so little nearness that it is often not even to be found at all initially. [...] That is also true, for example, of the street, the useful thing for walking. When we walk, we feel it with every step and it seems to be what is nearest and most real about what is generally at hand; it slides itself, so to speak, along certain parts of our body—the soles of one's feet. And yet it is further remote than the acquaintance one meets while walking at the 'remoteness' twenty steps away 'on the street.' Circumspect heedfulness decides about the nearness and farness of what is initially at hand in the surrounding world. Whatever this heedfulness dwells in from the beginning is what is nearest, and regulates our de-distancing." [60: §23, 99 [107]].

4.4 What Can Be and What Could Have Been: The Role of Counterfactual Statements in One's Experience of Space

Another important sense in which lived space implies an intentional relation with possibilities has to do with the role of *basic spatial principles*—comparable to the basic principles of logic, i.e. the so-called 'laws of thought' [see Russell 99: 72]—in one's experience of space, and the operationalization of these principles through counterfactual statements (i.e. subjunctive conditionals) shaping what one believes (or conceives) can be the case.

Space as one experiences it is undoubtedly something in which some states of affairs are presently the case: any conceivable spatial being is *currently* somewhere, in a given place with a given orientation. In that sense, its spatial properties are totally actual. The point is, however, that it is presupposed by one's experience of something as being *there*, say, of this table in the living room, that (1) it might not have been there, that is, the place occupied by the table could have been empty (and still can); and that, conversely (2), it might have been somewhere else: the table could have occupied another position (and still can).[35] This is a basic principle of spatial location: things occupy space, but the place they occupy is not cancelled as a place by their presence, the occupable place remains, 'behind' them, and it would have existed even if the object would not have been there.

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[35] These two statements express two sides of the same coin, considering that the relation which is at stake in the state of affairs 'occupying place P for an object O' can both be described as the relation: O is-occupying P, or as the symmetric relation: P is-occupied-by O. The claim that perceiving this state of affairs presupposes the two counterfactual statements indicated below is another way to say that this relation is, like in any other state of affairs, an *external* relation [3]. "A state of affairs exists if and only if a particular has a property, or a relation holds between two or more particulars. The relations are all *external* relations, that is, in no case are they dictated by the nature of their terms. In the jargon of possible worlds, it is not the case that in each world in which the terms exist, that is, in which the related particulars exist, the relation also holds." [3: 429].

An immediate practical consequence of this is that in principle any object can be *removed* from the place it occupies so as to free the place. This account is another way to express the widely acknowledged claim that places should not be conceived as reducible to the things they contain. As Casati and Varzi [19] explain, we cannot treat "the relation between an entity and its place—the place that it occupies or where it is located—[…] as mere identity, for we want to make sense of the possibility that the same place be visited by different things at different times". As a matter of fact, any place on earth has already been occupied by other things than these one currently finds there. To reuse an example from Sect. 2.1, we can say, typically: at *this place* there was a train station early in the century; today it is a traffic circle. Symmetrically, no object is bound to the place it is currently occupying; it is included in the sense (i.e. the conditions of identity) of spatial beings that they could have been elsewhere. This basic principle in one's awareness of space can be referred to as *the place contingency principle*: anything that is experienced as there is implicitly apprehended as something that could have been elsewhere while remaining what it is.

This principle means that perceiving space not only presupposes a commitment to what can be the case in the *future* (typically, what one can or cannot do: behavioural possibilities), it also, and more radically, presupposes a commitment to what could have been the case *now*. It is a challenge for phenomenology to understand how this kind of understanding is possible, what subjective mechanisms are implied in the ordinary belief—which is in fact more akin to *certainty*, in Wittgenstein's sense [see Wittgenstein 124: §.194 and §.208–209]—that any place could be occupied by something else, that 'behind' every occupant, there is an empty space. Some authors (typically Piaget) tend to explain this kind of understanding by equating it with (or deriving it from) a behavioural possibility we spontaneously rely on. This is turning things upside down in our opinion: if one expects that one can move something, it is because one believes that this something can be moved, not the opposite. I expect that I can move this chair because I have identified what I see *as a chair*, that is, something which, as any solid object, can change its place. The practical possibilities one relies on in perception are carved out into the possibilities delimited by the identity the perceptual objects have been ascribed. Another reason to reject the precedent thesis is that it is not because one cannot (effectively) move an object that this object cannot be moved (in principle). Note that what comes first in the developmental history of the subject is not the point here. Maybe the child learns first that *she can* move objects, and only later comes to apprehend objects as beings that are not bound to the position they currently occupy—i.e. acquires "a concept of bodies that can change place" [121]. In fact, it is more than likely. But what she has knowledge of, once this development achieved, is a logical order, an order of reason; and her understanding of this order cannot be reduced to a behavioural possibility, something she can do. Quite the contrary in fact: this logical order is now framing her knowledge of what she can do.

As a first approximation, this kind of cognitive ability or performance can be equated to a kind of pre-propositional form of counterfactual reasoning: to perceive that there is something there is to be aware (to conceive) that it could have been otherwise.[36] In that respect, only a type of mind for which what there is does not amount to what is currently the case can have the experience of something like a spatial world (but to use the term 'world' is already to think of something spatial). A living system that would merely be aware of what is currently the case, i.e. which would access *mere facts*, without putting them in perspective with what can or could have been the case, cannot be aware of something like a space. As a matter of fact, we can even doubt it can be *aware* of anything.

Other noteworthy principles can be mentioned playing a similar fundamental role in one's general understanding of spatial beings. What is generally referred to as the *principle of permanence* (or object permanence) in psychology, namely the fact that objects do not disappear when one cannot see them, undoubtedly belongs to this category. If I drop my fork under the table, it is *necessarily* somewhere, even if at first glance I do not see it. It *cannot* have just vanished. The same applies if you cannot find your shoes, your keys, your car, or your house. The belief in that principle, namely that material objects cannot just disappear (at least without a good reason), explains that one can spend a long time (perhaps one's whole life, if it is something other than a fork) searching for something. This principle is someway part of one's 'naïve physics' (or what could be called in that specific case one's naïve *meta*physics), namely the pre-scientific knowledge one has of the laws governing the behaviour of bodies and physical structures at one's scale [57].

What is remarkable is the compulsory character of this principle in our representation of reality, the irresistible role it plays in what Wittgenstein calls one's 'picture of the world' [see Wittgenstein 124: §93–95]. Material things cannot cease to be somewhere, they cannot disappear and then reappear, and in general they keep their place (see below). The point is that this principle (with other principles of the same kind) that regulates our intelligence of situations, works by shaping—and in a sense, limiting—the possibilities, it formats what one believes to be possible or not. Not everything can be. And what one believes to be the case in this or that situation, e.g. the possible scenarios one considers to explain to oneself what happened to an object, say one's keys, is always framed within the bounds of what one believes *can be* the case with this object. This is another decisive sense in which one's experience of space entails a commitment to—and is shaped by—possibilities.

A connected principle is the *principle of place permanence*, namely the fact that most material objects keep their place, i.e. stay where they have been left and seen; though they can certainly be moved, they do not move by themselves; and this principle precisely applies only provided things haven't been displaced.

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[36] Note that this can be accounted for in merely dispositional terms: to be aware (or conceive) that an object could have been elsewhere means to be disposed to behave or 'think' (e.g. form beliefs or intentions) in agreement with this statement. See Steiner [105] for developing such an account of what it means to possess or master a concept.

A noteworthy consequence of this principle is that place fulfills *to a certain extent* an identification function [see 19: 133]. What occupies a given place at instant t_2 is the same entity that was occupying this place at time t_1. This principle, like any other principle of this kind, is so deeply rooted in how one's mind makes its world intelligible, that its action can be easily overlooked. But this principle is behind any of our ordinary identification of objects. This cup on the table is the same cup that was on the table one second ago (it is not another cup), and it will remain the same cup it is in the next second. In addition, this same principle is what makes possible to apprehend that something occupying a given place is the same object despite sometimes substantial changes in its aspect or properties. Think of a piece of sugar disaggregating in a glass of water: what makes it appear as the same piece of sugar during the entire duration of the disaggregation process is the place it occupies. Remember Descartes' piece of wax.

The same holds considering one's practical understanding when coping with things. The chair before me in the kitchen is the same chair I saw and sat on in the kitchen this morning. The tree in the garden is the same tree that was at this place one month ago. This old white car spitting out grey smoke parked before my house is the same that was parked at this same place yesterday spitting out the same grey smoke. Of course, additional parameters come into the equation. For identifying the car as the same, some plausibility constraints must in particular be fulfilled. If I come back in twenty years and see a white car of the same model at the same place, I will probably not identify it as the same car, except if it presents a particularly discriminating element. The rules one uses to decide of the sameness of the objects one perceives are partly the result of a cultural process of knowledge acquisition. We can easily observe that before a certain age, children fail to identify certain objects as being the same, typically the moon in the sky, when seeing it at a few minutes interval. They do not yet know that on earth we only have one moon.

Similarly, the scale that applies when place works as an identity principle is variable and context-sensitive. This white mug is the same mug I use to drink my coffee every morning since several months for it is *in my house*. But it can be anywhere in it. If it happens that I do not find it where I thought I had left it but in another place, I will not apprehend it as another mug that looks exactly similar to the mug I know. For I know my memory is fallible and there are other people living in the house that could have changed its place. Conversely, I could see a mug with exactly the same aspect in a pawn shop and yet not identify it as the mug I know, for it is in a different place and I do not have at hand a plausible scenario explaining how it could have moved from my house to the pawn shop. If I suspect my wife to have sold our kitchen stuff, the situation is of course different.

This is an important feature to keep in mind when addressing the situation of blind people, for an essential difficulty blind people must deal with is the failure of the place-identity principle, which is due to the fact that objects fail to stay where they have been left because other people can displace them (see Sect. 6.1).

5 Lived Space and the Possibility of Being Perceived

Another important layer of lived space derives from a feature of one's being-a-body that has often been overlooked by phenomenologists, namely the fact that one can be seen or, more generally, perceived by others. One's body not only shapes lived space as an organ of action, it also shapes it by making one irrevocably *visible* to other embodied subjects.

When seeing others, we see if they look at us and we see if they can see us. I see that this man who is turning his back to me does not see me and cannot see me.[37] I see that I can no longer be seen by the people on the other side of the street for a bus is now blocking the view. And when in the kitchen I know (i.e. live in the implicit certitude) that my wife in the upstairs bedroom cannot see me. Lived space is organized along areas of visibility and invisibility, which are continuously renegotiated depending on where we are and where others are. And how we behave chiefly depends on whether we think we can be seen and are currently seen from where we are.

Many social places exploit this feature. The town square is an open-space where everybody and everything is visible to anyone; you cannot hide. The actors on the scene of the theatre are visible from any point of the auditorium, but the prompter is invisible, except for the actors. In the fitting room, the voting booth or the confessional, nobody can see you (except maybe the One who sees everything). In many shops you can see what's inside from the outside, which offers to make visible what you can buy. Conversely, some places are equipped with tinted windows, so that you can see the outside from the inside without being seen. Black glasses offer similar possibilities: the others cannot see where you're looking at. The principle of the panopticon, designed by Jeremy Bentham in the 18th century for the jails, consists in making visually accessible each cell from the central room, so that the guardians can keep an eye on everyone without having to move, but in making conversely invisible from the cells the central room. As a result, the prisoners are always visible for the guardians—they cannot lose their visibility–, but they cannot see if they are currently observed. This spatial organization prefigures the modern open spaces of office workers. The only difference is that there are (generally) no guards: everybody is in charge of watching the others. Joking aside, this last case illustrates an important spatial principle, namely that the configuration of space *in itself* forces the emergence of particular behaviours and is thus a way to act on these behaviours. As Foucault [40] explains, "the major effect of the Panopticon [is] to induce in the inmate a state of conscious and permanent visibility that assures the automatic functioning of power". In the case of open spaces also,

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[37] Claiming that being actually or possibly seen is something we *see*—and not *infer*, for instance—could be debated. This is however not the point here. To avoid any controversy, the former claim could be rephrased in terms of beliefs formed on the basis of visual experience: in many situations, when we see other people, we immediately form the belief that they see us or can see us.

it is quite obvious that the behaviours are directly impacted by the possibility of being continuously seen (thus spied) by others.

All those places and devices build on the fact that lived space is something we inhabit collectively—i.e. on its radically intersubjective character—and in which we are located as a visible body. The principles on which this layer of space –which we propose to call the 'mutual perceptibility space'—is built can be described, though, to the extent of our knowledge, this task hasn't been undertaken yet.

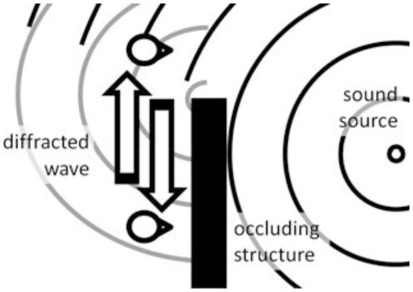
Whether others can perceive us from where they are primarily depends on how we are located in space with respect to each other, and on the arrangement of physical structures between us. In order to see if someone can see me from where she is (assuming she looks in my direction), I must see if her gaze can reach me, which depends, above all, on whether there are opaque surfaces, i.e. visual obstacles, between us. (Note that being seen does not necessarily imply being stared at: one can be seen peripherally.)

A principle we frequently use to determine if we can be seen is the principle of reciprocity, which can be expressed as follows: if I can see you, you can see me. To some extent, this principle is a consequence of the laws governing the propagation of light. This principle does not apply in every type of environment, however. Typically, it does not apply if I am located behind a one-way mirror or look at someone through a video monitoring device; in this case, I can see you, but you can't see me. Similarly, if I am looking at someone when in a crowd (e.g. an actor on the theatre scene from a crowded audience), I will spontaneously hold that she cannot see me. For sure, she *can* see me in the sense that I am visible for her, but it is unlikely that she will look at me rather than at somebody else. I am, as we say, hidden by the crowd. Our respective visual exposure is dissymmetric.

The same can be held for the possibility of being heard. I can hear that somebody else does not hear me if she does not reply to something I said (and if I expect that she should have if she had heard me). Checking if others hear us is quite common, e.g. when talking to old persons going deaf, or to younger ones wearing headphones, or to somebody in another room, in the distance or in a noisy environment. Similarly, when someone sleeps in the next room, one tries not to make noise only because one believes that one can be heard.

Audition and vision are not completely the same, however, for if we can quite easily see if others *can* see us, it is far more difficult to hear if others *can* (pay attention to the term) hear us. In order to hear whether one can be heard (from where one is), one must access aurally to something (a physical structure or a configuration of the environment) that affords not being heard. I can hear if you answer me when I talk, or I can hear that the sounds coming from this room stop or are muffled now that I have closed the door. But I do not access aurally to a configuration of the environment that could make me anticipate that you can or cannot hear me from where you are *before* any conversation. I *see* that there is a window between us (I could also feel it with my hands); and I hear that I do not hear any sound coming from behind this window; as a result, I form the belief that you *cannot* hear me from where you are (the same applies if you are too far for me to be heard). Keep in mind that this belief is about what you *can* hear, i.e. your perceptual possibilities, not about what you are currently hearing.

Note that in principle, it might be possible to extract this kind of information through audition alone, when the sense is used with an echolocation function [51, 108, 109, 119]. With enough training, one can perceive through echolocation that there is a structure ahead, e.g. a wall, a door or a window, that blocks the sounds and enables not being heard. One can move back and forth along this structure (or open and close the door) so as to make appear and disappear some sounds coming from behind. Assuming a reciprocity principle, one can infer that when one is hidden behind the structure one cannot be heard from the points of space from which these sounds come. Echolocation is however limited compared to vision, in this respect: a complete auditory occlusion is as a matter of fact difficult to create, because of the mode of propagation of sounds, which differ from that of light rays which follow a linear trajectory and can be easily blocked. In addition, echolocation can barely provide access to multiples structures at different distances and occluding each other (there is no real *depth* in hearing), which can be easily perceived with vision. We will come back to this point in Sect. 6.2.



These perceptual laws are an important ingredient in our ordinary understanding of space. We have some naïve knowledge of the perceptual (e.g. visual and acoustic) laws that condition perceptual accessibility. And we have some models of the range of the perceptual apparatus of others, i.e. of the areas of space that can be accessed visually or aurally by them from where they are. In addition, we are sensitive to the many perceptual cues suggesting that we are currently perceived by other agents. How their sensory organs (e.g. their eyes) are oriented relative to us is a key parameter. But there are many others. In general, the behaviour of others, in the sense of their body attitude, will be perceived as the sign that they perceive us, if it is connected in a reciprocal way to one's own behaviour, that is, if there is a contingent interaction: how the other behave is contingent upon how I behave, and vice versa [7, 76]. Eye contact is a paradigmatic case.

Note, however, and this is a key point, that lived space is already structured as a medium conditioning mutual perceptibility *before* any other subject comes into play and even if there is nobody around. Mutual perceptibility space deals with mere possibilities: it is a ‘model’ of whether one *can* be seen or heard from where one is, but it does not include knowledge about whether one is *currently* seen or heard by this or that particular other. The distinction is important, because perceiving whether one is currently perceived results from special mechanisms, which most of the time can only work based on the mutual perceptibility space. I see that my current location can be accessed visually (only) from this or that area, that is, someone that *would* be there *could* see me. But additional conditions must be fulfilled when someone is effectively occupying these areas for me to perceive that she is currently seeing me: I must see that she is oriented to me, that her eyes are open, that she’s looking at me, etc. Many of these perceptual parameters are related to body orientation and attitudes. These elements are not included in mutual perceptibility space, which only delimits the regions of space from which one *could* be seen.

The mastering of mutual perceptibility space presupposes, in addition, that we have an adequate ‘model’ of our body dimensions, something like what is referred to as the ‘body schema’ in psychology [42, 58]. It is quite obvious that children under a certain age lack such model or still have an inappropriate one, as demonstrated by their attempt, when playing hide and seek, to hide behind structures too small for their body. The hiding affordance offered by the object is not yet scaled on their body dimensions. More generally, for a long time children lack an understanding of the spatial conditions that must be fulfilled for other persons to perceive what they perceive. Children under the age of four or five will for instance ask your opinion about things (typically, toys they are playing with) you cannot currently see because you are in another room or on the phone. The same holds for being heard: in a noisy environment, they can talk to you because they see you’re there, without understanding that you cannot hear them from where you are.

Modern technologies, such as video surveillance and satellite scanning systems, or, considering the aural channel, microphones, are also structuring our mutual perceptibility space. The basic point with these devices is that they break, to a certain extent, the spatial constraints that are ‘normally’ associated with mutual perceptibility: where the other perceiving agent and the surveillance device are located relative to the person who is observed does not matter, they could be at several meters or on mars, it does not change anything. The spatial constraint is not erased, however, but it is shifted on the spatial relation between the person who is observed and the capture device, whose range is more or less important. And it is this spatial constraint that structures the mutual perceptibility space. The thief sees that the camera cannot see this part of the store. James Bond puts some loud music on before starting to speak to Felix Leiter for he suspects his room is full of microphones.

6 The Space of the Blind. Do Visually Impaired People Live in Another Space?

In this last section, we will draw on the phenomenological elements analyzed in this chapter to address the question of how blind people experience space. To put it in a nutshell, we have seen that:

(i) space is experienced as a set of interconnected places (a kind of network) defined by social practices and means of accessibility (Sect. 2);
(ii) lived space is shaped by one's bodily skills; the spatial arrangement and spatial features one is aware of at each moment constitutively depends on one's being-a-body and one's capacity to act through this body (Sect. 3);
(iii) one's experience of space in perception is essentially determined by an anticipation of, and commitment to, possibilities: one perceives space, places, distances, because one foresees what can and cannot be; this can be rephrased the following way: the content of one's spatial perception must partly be specified by appeal to counterfactual statements about one's practical possibilities and the possibilities describing how the things in space could be otherwise located (Sect. 4);
(iv) lived space is shaped by one's consciousness of being visible (or more generally perceptible) by others; that is, the many possibilities shaping one's experience of space include the possibility of being perceived by others (Sect. 5).

Considering the various parameters playing a critical role in the shaping of lived space, it is reasonable to expect that sighted and blind people should experience space in a very similar way. You do not cease to have a body that can move because you cannot see, you do not cease to intend objects as being more or less accessible depending on where they are, and you do not cease to experience space as organized as a network of interconnected places with allotted functions, offering different possibilities, with different social status and atmospheres. The same can certainly be held for what regards the possession of most spatial concepts and for spatial reasoning. As Landau [74] explains—and this is now widely agreed upon[38]–, "certain principles of spatial knowledge arise independently of the particular avenue of experience. That is, the blind and sighted develop identical principles rather early in life, despite their very different encounters with the world." So, where are the differences? Is there *any* difference except that space is not *seen* by blind people? As a working hypothesis, the following proposal can be made, which is related to a particular interpretation of the specificity of vision against

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[38] Note that this claim only applies to the development of spatial concepts, and does not mean that there are not differences in spatial cognition between the blind and the sighted [112]. For instance, it is now widely acknowledged that blind people extensively rely on egocentric coding to orient themselves in space and have difficulties with allocentric spatial representations [see e.g. 13, 115]. See however Lewis et al. [77] for qualifying this claim.

other modalities: compared to the space of sighted people, (i) the space of the blind is poorer in terms of currently available possibilities and is more internalized (6.1); (ii) the space of the blind is lacking some principles of organization (or their role is largely diminished), some of which play a critical role in social relations, such as the principle of occlusion (6.2).

6.1 The Memory-Dependence of the Space of the Blind

A first claim we can put forward to try to catch the specificity of the kind of space blind people live in is that it relies to a substantial extent on memory and other representational abilities (see the Introduction section for this notion). In other terms, the space blind people live in is much more ‘internalized’ than the space of sighted people. Surely, the spatial environment is also *present* for the blind person: the space around is not something she is thinking about (i.e. something that is represented, as when recalling a place where one lived), it is there now, and she experiences herself as located within it, just as sighted people; but to deal efficiently with her environment the blind person must constantly make use of her memory to keep track of what is there and where things are.

Vision enables what could be described as an externalized awareness of the varieties of possibilities made available by the environment, the spatial layout and the objects. When tapping on the computer, the room with its familiar equipment and related opportunities are visually present in the background. I see what the environment affords and where the objects are. Or, to put it a bit differently, I *know* what the environment affords and where the objects are because it is explicitly visible, i.e. the information is available and can be accessed if needed [89]. I do not have to memorize the position of my cup of coffee on the table, for I just have to look to know this position. The visual space itself works as an external memory [90].

Because they cannot rely on this immediately available external memory, blind people have no choice but to keep track of everything, that is, the spatial arrangement of the environment and the places of objects must be known: this availability through knowledge can be based on explicit place memory (remembering that the pen is on the top of the shelf), but also on a more implicit way, e.g. the practical expectation that a given object is where it has always been (the kitchen table at this location in the room), that is, on automatic body habits. In other terms, blind people must replicate ‘inside’ the spatial arrangement of the ‘outside’: they constantly need a mental map.

It is obvious that the only way to manage this task with reasonable performances is to limit (drastically) the number of things in the environment and be very organized: everything must have a place and remain in its place. The strategy some blind people use to clean the floor is a good illustration. How to achieve this task without seeing what parts have already been cleaned and what parts haven’t? When you see, you just have to look. When you don’t, you must memorize.

But your memory is limited and subject to interferences. Most blind people achieve this task by moving in a grid type pattern: this hyper-rational strategy not only ensures that no part of the floor will be forgotten or cleaned twice, it alleviates the tracking task and make it more robust to interferences. This can probably be taken as a general rule: how blind people arrange their lifeplace follows from the requirement that the places allotted to objects can be easily and reliably remembered.[39] They have to continuously tidy up their environment, both in a concrete and a representational sense.

Sighted people generally follow the opposite principle: they rely as much as possible on the external memory their visual access provides to keep track of where things are. That is, they only store in their 'internal' memory elements that cannot be directly 'stored' in the environment's external memory or they will store indications (e.g. memo) that are necessary to make use of the environment *as* an external memory [23]. Why should I remember where I put my glass considering I can immediately *see* where it is? The lifeplace of many sighted people is a mess because disorder is something they can deal with, considering their cognitive equipment.

An additional objective of the lifeplace arrangement of blind people—this is another hypothesis we propose—is to secure the principle of place permanence according to which 'things are still where they have been left' (see above, Sect. 4.4). Of course, this requirement only applies to movable objects, not to objects fixed on an immovable support, e.g. a wall switch, a door handle, a wall cabinet. But most of the things we make use of are displaceable, and a condition to use them is to get hold of them. In that respect, living in collectivity can be a real challenge for blind people, the presence of others in the lifeplace equating to more entropy, which puts additional perturbation on the principle of place permanence they must fight to preserve. Keeping track of where objects are through memory is useless if the objects do not stay where they have been left. This is true for the key you have put on the table (not on the wall key hook) and the butter you have stored in the kitchen cupboard (not in the fridge), but also for the chair you have put that particular way under the table to avoid any future collision.

One of the most difficult (and irritating) tasks for blind people is to search for an object that is no more where it is supposed to be. One blind women (L.) we have interviewed[40] explained that she always puts the fruit yoghurts on one side of the fridge and the plain ones on the opposite side (yoghurts boxes have generally the same shape and can barely be discriminated on the sole basis of touch). But this simple rule is useless if it is not applied by the other users of the fridge.

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[39] Note that the field of situated cognition offers important theoretical resources to deal with these questions, especially the notion of 'complementary strategy' [69, 73].

[40] We thank her for having helped us toward a better understanding of the experience of blind people.

6.2 Can Blind People Hide? The Principle of Perceptual Occlusion in the Blind

Another peculiarity of the spatial cognition of blind people that can be diagnosed is that they apparently show difficulties in conceptualizing the principle of occlusion (or inter-position), namely the possibility for something to be hidden or masked because of the presence of something else.

The principle of occlusion fulfills a pivotal role in the construction of the mutual perceptibility space, for being hidden by something (typically, a wall) is a basic way to escape the eyes of others (see Sect. 5). We can thus expect the mutual perceptibility space of the blind to show distortions compared to the sighted.[41] This claim must however be taken with caution, for it obviously does not apply equally to congenitally blind, early blind and late blind persons, and inter-individual differences are probably important. In addition, though occlusion undoubtedly plays a central role in the organization of visual experience, it can hardly be reduced to the visual universe. The existence of non-visual forms of occlusion is for instance accredited by everyday language. One can mask a bad odour with perfume. One can mask a sound with a louder one. One can mask one's emotions or desires. And one can mask the truth. Moreover, congenitally blind people have obviously a sense of what part of themselves can be seen or what part cannot. They also exhibit some complex understanding of the meaning of sentences with terms related to vision (e.g. 'see', 'look'), which indicate that they understand the spatial constraints on the visual access to something, typically that you cannot see their back unless they turn their back to you [see 74: 360 sqq.]. Some data suggest, in addition, that blind people can understand visual occlusion when exploring tactile images [72]. This is also true for all that is related to the domain of privacy or intimacy. And—though it is not a spatial fact in the strict sense—blind people undeniably know their mental states are not something 'visible' to others. (It is worth noting, however, that this kind of knowledge can have peculiarities compared to the knowledge sighted people generally have. Some blind people may for instance feel surprised when they come to learn that most emotions are visible on the face.[42]) As far as we know,

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[41] The fact that some blind subjects have impairments in representing the perceptual point of view of others, i.e. what they perceive from where they are, supports this view. Miletic [83] has for instance observed that congenitally blind children show severe difficulties in a perspective taking task. Hollins and Kelley [64] find similar results in blind adults. But see Heller and Kennedy [63] for contrastive data.

[42] Ville-Gilon [117], who has performed a series of semi-directed interviews with blind people to investigate how they understand and deal with their visibility, for instance explains: "During a sculpture session L. was asked to touch the face of statues: a face contorted in pain or expressing joy, or laughing, or crying, etc. She told me that she was suddenly aware that emotions were 'seen from the outside' and that she believed until then that for an emotion to be visible on the face of someone it had to be 'deliberate'. She thought that a face as such was 'frozen', and that it was consequently useless. She said that now she was 'careful not to show everything'." (Ville-Gilon [117], our translation) Note that L. is approximately 45 years old.

data about the capacity of blind people to conceptualize their own perceptibility and the possibility of being hidden from others is however lacking, and this is this specific issue that we wish to examine in the following. The point is that if occlusion can surely be conceived through other perceptual modalities than vision, these modalities probably cannot substitute for the kind of 'visibility' that is enabled by visual perception: in short, vision makes one *visible* in a way that other modalities cannot replace.

Is it possible to develop an understanding of the principle of occlusion without vision? Note first that being occluded is not the same as being out of view (i.e. too distant to be perceived) or absent. What is occluded is there now and visible but it cannot be seen because of the presence of something else, which 'blocks' the access. Occlusion essentially involves a counterfactual statement about the perceptual accessibility in other conditions of what is currently hidden. In order to apprehend that something A is occluded by something else B, one must believe or expect that *if B was not there*, one would perceive A from where one is (i.e. without changing one's position).[43] But one must in addition conceive of the occlusion relation as the result of a spatial arrangement, literally an *inter-position*: for B to mask A, in a way or another B must be located *before* A. In order to perceive occlusion it is thus necessary to access perceptually to something like a depth, the simultaneous presence of a series of positions arranged in a before-behind order. This possibility is obviously lacking in touch which is subordinated (by definition) to contact relations (you only touch what you are in contact with). You cannot find it in olfaction either, which obeys similar principles as touch (this is a contact sense). Is it possible to develop an understanding of the principle of occlusion through hearing? Hearing seems in a better position to fulfill the above prerequisites. Hearing is like vision a sense of distance that enables to access something like a depth: by hearing you can access simultaneously multiple sources of sound at different distances, and you can certainly conceive that a sound masks another one, i.e. makes it inaudible. The problem remains, however, of the spatial character of this masking relation. When a sound is masking another, this is not primarily because of the respective positions of the sound sources, but rather their respective intensities at the position one occupies. As a matter of fact, a sound source can be more remote than another and mask the latter just because it is louder. I cannot hear what John, who is right beside me, is saying because the speakers over there are playing too loud. However, audition makes it possible to conceive a real occlusion relation with non sound-emitting structures. One can prevent a sound from reaching one's ears by blocking its diffusion with a physical obstacle, e.g. by closing a door. And, as we have seen in Sect. 5, the so-called 'obstacle sense' (i.e. echolocation ability) most blind individuals rely on to locate, based on auditory input, distant objects [see e.g. 4, 109, 111], could in principle be used to perceive that the

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[43] It does not mean that occlusion is something you cannot *perceive*, but must conceive or imagine. As seen in Sect. 4, counterfactual commitments are constitutive of perceptual experience: to perceive is always to expect that if this change occurred in the perceptual circumstances, that change would follow in the perceptual content.

presence of a physical structure prevents the auditory access to what's behind. In a similar way, some experiences of causality (more precisely, of the dependence of perception upon a causal chain going from the source of stimulation to the sensory organ) seems able to provide access to the principle of occlusion. We can stop the causal action of the environment on us—noise, heat caused by sunlight, rain—by interposing a blocking structure or 'hiding' behind something—under a roof, an umbrella, behind a wall, or by covering our ears. These experiences are definitely accessible to the blind.

Note, however, that an apparently irreducible gap between these different types of perceptual occlusion and visual occlusion is that they can only incidentally imply one's own 'visibility' to other subjects (to make use of a term from the visual domain, which has assuredly a paradigmatic role here). In the different situations addressed above, what is blocked is one's perceptual access to an object; but the symmetrical situation, namely the situation where *oneself* is the object to be perceived (or what exerts a causal influence on someone else), is more difficult to conceive in non-visual modalities. In other terms, realizing that we can hide from the others behind occluding structures seems to be, first and foremost, a visual achievement. Once again, this claim must be qualified, for auditory perception seems able to fulfill this role to some extent. If I make noise I can prevent being heard by others by interposing a physical structure between us, typically by closing a door. A difference that seems irreducible, however, is that we do not control, or only marginally, our visibility (we cannot cease to be visible—though we can cease to be seen), whereas in the vast majority of cases, we control the sounds emanating from our body. If our body was constantly emitting a sound—which was, in addition, characteristic of oneself, as is our visual aspect—, the situation of auditory occlusion would offer similar perceptual possibilities than the situation of visual occlusion. We cannot depart from this visibility, and we are, as a result, constantly exposed to the perception of others: even when there is nobody to see us, we could be seen. We cannot hide, and this impossibility deeply affects the space built by the sighted.

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Technologies to Access Space Without Vision. Some Empirical Facts and Guiding Theoretical Principles

Charles Lenay and Gunnar Declerck

A large number of technical devices attempt to help blind persons improve their spatial perception and facilitate their mobility. We wish to present here the principles on which these prosthetic perceptual devices function, the conditions of their appropriation, and the general perspectives they open concerning the role of technical objects and systems in the constitution of human experience. A technical device for assisting perception has to compensate for a sensory deficit by mobilizing other subsisting sensory modalities which remain available. We therefore have to understand the relationship between perceptual activity and sensory input. In addition, we shall see that the technical devices which assist perceptual activity can in return serves as tools for experimental scientific research on the mechanisms of perception in general.

The analyses presented in the preceding chapter seem to show that perceptual experience of the space which surrounds us is the experience of the availability of a system of actions, in other words an organized set of possible journeys and operations that can be performed in the world. Whatever the sensory modalities that a subject has at her disposition (be they visual, auditory or tactile), we can suppose that her perception of a space which surrounds her corresponds for her to the presence of a field of possibilities of this sort, which enables her to localize objects, to choose gestures and movements, to decide which actions to perform, etc. The tools and prosthetic devices she can use aim at modifying and enriching this field of possibilities, which will give access to new actions and perceptions. Our aim in this chapter is to propose several hypotheses to explain the mechanisms by which

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perception can be transformed according to the tools and prosthetic devices employed, and to show that in each case this transformation amounts, finally, to a reconfiguration of a field of possibilities. To do this, we shall start from the extreme situation of the so-called ‘sensory substitution’ systems; we will then decline several variations so as to better understand in each case the way in which the technical mediation transforms the relations between sensation and perception, and thereby modifies the field of accessible possibilities.

1 Sensory Substitution

The so-called ‘sensory substitution’ devices correspond to the ambition, which may seem naïve, to replace a deficient sensory input by another modality which is still functional. A more detailed presentation of these devices in all their diversity will be given later (Chapter “Scene Representation for Mobility of theVisually Impaired”). Here, we will focus on the most emblematic and most radical device of perceptual aid to compensate for the absence of vision: the Tactile Vision Substitution System (TVSS) proposed by Paul Bach y Rita at the end of the 1960’s [4, 5]. The TVSS consists of a square matrix of 400 tactile stimulators connected to a digital camera. The image captured by the camera is simplified and converted into black and white pixels (without intermediate grey levels), and then used to control the activation of a ‘tactile image’ of 20 × 20 pixels, i.e. 400 tactile stimulators which are raised or not according to whether the corresponding element of the image is black or white. This tactile matrix is applied to the skin, either on the back (the first version), or on the chest or the forehead [13], and more recently on the tongue [7, 9] (Fig. 1).The first trials with this sort of device provided three fundamental results.

(i) First of all, the presentation of shapes to an immobile camera procured only a very limited discrimination of the tactile stimuli, which were perceived as being on the surface of the skin. Thus, the simple substitution of a sensory input through the optic nerve by a tactile entry does not, in itself, give access to a spatial perception.

(ii) However, if the user was active (moving the camera by translations and rotations, and zooming), he developed spectacular capacities for recognizing shapes. After 15 h of practice, he discriminated increasingly complex familiar objects, to the point of being able to recognize faces.

(iii) Moreover, this capacity to recognize shapes was accompanied by an *external projection* of the percepts. The user no longer felt tactile stimuli on the skin, and instead perceived stable objects ‘out there’ in front of him in a three-dimensional space [5]. The perception of a stable object ‘out there’ is quite distinct from the succession of variable sensory stimuli that the subject receives as he constantly moves the camera. The blind person begins by learning how variations in his sensations are related to his actions: when he

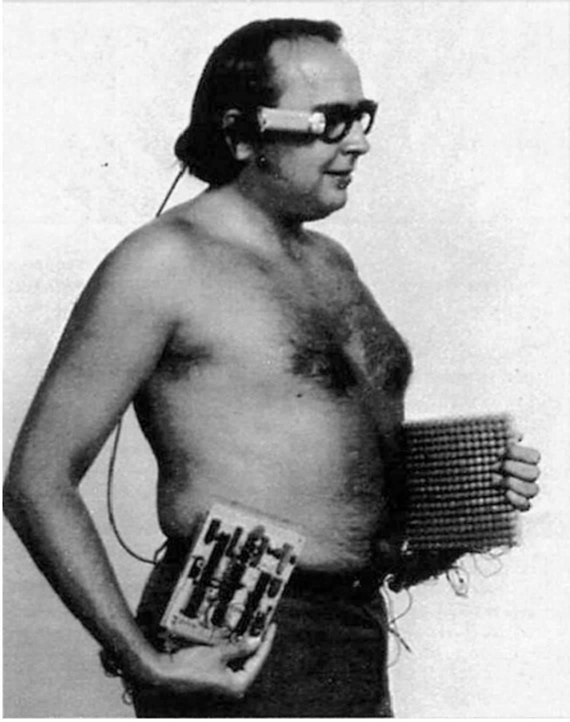

Fig. 1 The tactile vision substitution System. Here the matrix of 20 × 20 tactile stimulators is placed on the chest and the camera is placed on the frame of a pair of spectacles

> moves the camera from left to right, the stimuli on his skin move from right to left; when he zooms forward, the stimuli move apart, etc. He also discovers perceptual concepts that are new to him such as parallax, shadows, occlusion, etc. Certain classical visual illusions are spontaneously reproduced [6, 24]. This sort of experiment can be performed not only by a blind person but just as well by a sighted person who is blindfolded.

Through these initial results, we see that a whole set of very fundamental questions are posed concerning perceptual learning, the localization of objects in a distal space and the recognition of shapes. It therefore seems to us that study of this very particular extreme situation of sensory substitution could be useful for shedding light on the general problems involved in the appropriation of perceptual aid systems. Indeed, this sort of device makes it possible to follow the genesis of a novel prosthetic perceptual modality; and in particular, to follow the constitution of a *space of perception* in which objects can be perceived as being external [1, 38]. One can then carry out in parallel an objective analysis in a third-person perspective of the resolution of perceptual tasks, coupled with the description in a first-person perspective of the corresponding lived experience.

We will first of all examine the question of spatial localization and the perception of the three-dimensional space which surrounds us; we will then study the perception of shapes and arrangements in the two-dimensional space of writing and reading; before concluding in a more general way on technical mediation of perception.

2 Spatial Localization

2.1 The General Problem

In the course of learning, the TVSS user first of all feels the successive stimulations on her skin. However with the progressive use of the device, she ends up forgetting these tactile sensory inputs and comes to perceive stable objects at a distance, out there in front of her. The very first device transmitted the tactile stimuli to a matrix placed on the back. Bach y Rita thereupon remarked: ‘When asked to identify static forms with the camera fixed, subjects have a very difficult time; but when they are free to turn the camera to explore the figures, the discrimination is quickly established. With fixed camera, subjects report experiences in terms of feelings on their backs, but when they move the camera over the displays, they give reports in terms of externally localized objects in front of them.’ [49: 25] Thus, according to the witness accounts of the users, the proximal irritations provoked by the tactile plate are quite different from perception as such [5, 42, 48]. The device and the tactile sensations it procures are no longer perceived as such, when the device procures a perception of objects in a distal space.

What we want to understand, then, is this appropriation which occurs by a sort of ‘switch’ in perceptual experience, which started out as a series of proximal events, i.e. the tactile stimulations, and which at some point becomes centred on objects which are separate from the body and which are situated in a distal space. One of the keys to this transition seems to be the activity of the perceiving subject, the movements of the receptor system (the camera). But what exactly is the role of these movements? *How* does this activity participate in the emergence of a distal perception?

Two main approaches are possible.

(i) First there is a representationalist approach, according to which one considers that the actions of moving the captor have the sole function of acquiring relevant information (in this case, mainly information about the relative positions of the body and external objects) in order to construct an internal representation [10]. According to this view, the actions are not properly constitutive of the perception (if equivalent information could be obtained *by means other than action*, there could quite well be perception without action).

(ii) Alternatively there is an enactivist approach, where one considers that the actions are indeed constitutive and therefore absolutely necessary in the very course of the perception of the distance of the objects. On this view, the

> perceptual experience results directly from the sensory-motor dynamics, without any need for recourse to the intermediary step of representations.

For the first, representationalist approach, the sequences of activation of the matrix of tactile stimulations makes it possible to progressively infer the distal spatial coordinates of the perceived objects. The question of the proximal-distal switch is then understood as a problem of 'distal attribution' [15, 33], namely 'the ability to attribute the cause of our proximal sensory stimulation to an exterior and distinct object' [1: 506]. Distal attribution would be a solution to a *causal inference* problem, because the most likely environmental cause of incoming vibro-tactile or electro-tactile stimulation—contrary to the default haptic interpretation—is a distant scene. This position belongs to what is traditionally called the 'representationalist-inferentialist' approach to perception: perceiving is equivalent to constructing (or inferring), on the basis of the available sensory data, a representation of the objects which are supposedly the cause of these sensations [16, 21, 22]. 'Perception' is a process of elaborating hypotheses; its functioning is basically heuristic and probabilistic.[1] We may note in passing that this conception is not incompatible with certain sensori-motor approaches to perception (see for example [40]).

However, this way of considering the phenomenon of the proximal-distal switch is debatable, in the sense that the problem here is not to *attribute* the incoming tactile data to external causes. Right from the start, there is a form of distal attribution, since the novice user of the TVSS is quite conscious that the pressure on her skin is produced by something external to her body, i.e. the matrix of tactile stimulators. The tactile sensations are not brute data which have not yet achieved a 'representational' function (or a 'figurative' function as Husserl would say). Via the 'tactile data' it is already an objective environment which is perceived by the user: a set of pressures exerted on her skin. The point is rather than these pressures cannot yet be deciphered in terms of objects located in the environmental space (for example 'a chair over there') or a spatial configuration of rooms (for example 'a corridor', 'a door', 'a wall'). It is like when one looks at a figurative picture without yet having succeeded in seeing what it represents, and one only perceives in the beginning a system of shapes without any 'meaning'. Auvray and Myin [3] quite rightly compare sensory substitution to reading: before they have appropriated the device, sensory data are like the words of a language that one does not speak.[2]

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[1] "The content of the perceptual state formed in response to a particular pattern of stimulation—the brain's operative 'hypothesis' about the structure of the impinging environment—is the cause to which the highest probability is assigned given all the available endogenous and exogenous evidence. In the case of vision, this will normally be one of indefinitely many possible three-dimensional scenes." (Briscoe, *forthcoming*: [10:6]).

[2] But, as Heidegger insists: "It requires a very artificial and complicated frame of mind to 'hear' a 'pure noise. […] In the explicit hearing of the discourse of the other, too, we initially understand what is said […]. Even when speaking is unclear or the language is foreign, we initially hear *unintelligible* words, and not a multiplicity of tone data." (Heidegger 1927, §.34, p. 153 [p. 164]).

For the second sort of approach, that may be termed enactivist, the activity is an indispensable component, not only for learning the prosthetic device, but also for achieving the perceptual experience as such. Spatial perception is constituted as much by the actions performed as by the variations in sensory input that they occasion. From this point of view, the phenomenon of the perceptual switch is not a problem of 'distal attribution', but corresponds to an alteration in the sensori-motor dynamics, the passage from a dynamics of the constitution of a perception of contact to a specific dynamics of the constitution of objects at a distance in space.

In order to discuss the relevance of these two approaches, and thus to clarify the status of action and the way in which the use of a tool can lead to the perception of objects in a distal space, we have employed a minimalist method.

2.2 A Minimalist Method

Our minimalist method consists of using the simplest possible perceptual device, in which the repertoires of action and the sensory feedbacks are drastically reduced to a bare minimum. The first point was to verify that the phenomenon of distal perception still occurs in these impoverished circumstances. This makes it possible to control quite precisely what are the objects that can be constituted in each case, and what are the operations that are necessary for this constitution. We have thus reduced the system of Bach y Rita to a single photo-electric cell connected to a single all-or-nothing tactile stimulator. When the total luminosity in the incident light field (a cone of about 20°) is greater than a certain threshold, the tactile stimulus is triggered (Fig. 2).

At each moment in time, the subject (who is blind or blindfolded) thus receives only minimal information, 1 bit corresponding to the presence or absence of the tactile stimulus. We have been able to show that even with such a simple device, the spatial location of luminous targets was still possible [28]. Initially, the subject only perceives a succession of tactile stimuli which accompany her movements. But quite soon, as she becomes familiar with the device and starts to master it, she no longer notices these sensations which are replaced by the perception of a target at a certain distance in front of her. Here, it is quite clear that perception cannot be

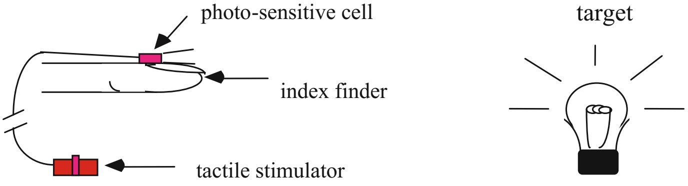

Fig. 2 The minimalist experimental device for spatial localization. The photo-sensitive cell is fixed on the index finger. When the amount of light received is above a certain threshold, the cell activates a tactile stimulator (that can be held in the other free hand)

grounded merely on an internal analysis of the input data (namely, the tactile input); the latter is simply a temporal sequence of all-or-nothing 1's and 0's which has nothing intrinsically spatial about it (contrary to the two-dimensional organization of the stimulators in the TVSS matrix).

It is quite understandable that it is possible to locate the target, even if the movements of the subject are simplified, and reduced to movements of the arm around the shoulder articulation, and movements of the hand around the wrist articulation. In Fig. 3, we consider only movements in a horizontal plane (three-dimensional space can be recovered by integrating up-and-down movements in the vertical plane). The situation is represented in (x, y) coordinates, with the subject place at the origin (0,0). The target is a point source, S, situated at a distance L from the subject with coordinates (0, L). The point P designates the wrist of the subject; its coordinates are ($b.\cos\alpha$, $b.\sin\alpha$), where b is the length of the arm, and the angle α = (Ox, OP) indicates the orientation of the arm. The angle at the wrist, between the arm and the hand, is designated by β = (PO, PS).

We may suppose that the subject is oriented with her chest facing the target, and finding a tactile stimulation with the arm point straight forwards and the finger aligned with the arm ($\alpha = 90°$, $\beta = 180°$). From a strictly mathematical point of view, a single pair of additional values (α, β) is then sufficient to determine the distance L. As shown in Fig. 3, L is given by a simple trigonometrical formula, if we consider that b, the length of the arm, is known.

In order to account for the perception of the position of the target, it therefore seems plausible to suppose that the subject relies essentially on the proprioceptive data concerning the positions of her limbs to construct an internal representation of the relation between the position of the captor at the end of her finger and the position of the target (an operation of triangulation [12]). The actions would serve only to establish this relation by allowing for an exploration of the scene (movements which in addition facilitate a more precise proprioception). In this case, the

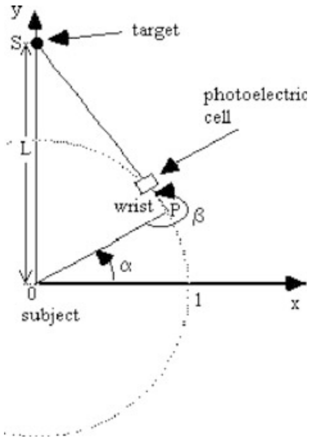

Fig. 3 The arm (forearm included) has a length b. The distance to the target L (0S) is given by the trigonometric formula: $L = b(\sin\alpha - \cos\alpha \tan(\alpha + \beta))$ (Eq. 1)

calculation of the position of the target would only require pointing at it a few times, several pairs (α, β) to inscribe the object in a space of internal representation.

However, observation shows that in order to maintain the perception of a target placed in front of her, *the subject must act continually*, moving the photo-electric cell so as to aim at the target in different ways. This can easily be understood if we look at things from the phenomenological point of view of the subject. As soon as the movements stop, the perception disappears. If she is immobile, there are only two possibilities: either she receives a continuous stimulus, or she does not. If she is pointing away from the target, she has only the memory of a perception which fades away. If she is pointing at the target, she receives a continuous sensory stimulation—but this does not give rise to the perception of an external object. On the contrary, consciousness is now filled by the presence of the tactile sensation as such.

If we wish to explain the necessity for this incessant activity in a representationalist approach, one might try to explain it by the need to constantly reactivate the sensitivity of the sensory cells which otherwise (by virtue of rapid adaptation) might cease to send signals to the central nervous system. However, the phenomenological description shows that if perception ceases when the concrete activity of moving the hand stops, it is not because the sensory data evaporate, but on the contrary because the tactile stimulation *as such* becomes only too present, thrusting the perception back on the place where it is directly felt. Here, there is not distal perception without action because spatial perception requires a constant *synthesis* of a temporal succession of actions and sensations.

If one admits this essential role played by action in the emergence of perception, then it must be admitted that what is perceived, recognized, is not really the invariants extracted from the sensations, by rather the invariants of sensori-motor loops related to the activity of the subject. This involves abandoning the passive conception of perception for which the system would receive as input certain information and then carry out a calculation to identify the objects and events before going on the produce representations in an internal space. On the contrary, perception is accomplished by mastery of sensori-motor regularities. The theoretical framework of active perception has been variously developed in the ecological approach to perception [19, 20, 46], and in sensori-motor or enactive approaches [11, 36, 37, 39, 41, 47]. By her action the subject seeks and masters the constant rules which relate action and sensation. The perception of an object consists in the discovery of regularities in the relation between variations of action (mobility of the organ of perception) and variations in sensations (produced by these actions), it is what Kevin O'Regan calls a 'law of sensori-motor contingency' [37]. The richness of perception should thus depend at least as much on the capacities for action (mobility, rapidity, zoom, etc.) as on the variety of sensory inputs (width of the spectrum, number of sensors, etc.).

As we have seen, in our minimalist experiment at least, there is no perception without action. One observes that the subjects perform regular oscillations around the target: generally small oscillations of the hand (β), accompanied by larger movements of the arm (α) which cause progressive changes in the position of the wrist. It is as though the subjects seek to identify and verify the functional relationship between α and β which must be respected in order to obtain a sensory feedback. There is perception of the position of the target when the subject masters the sensori-motor rule allowing him to aim at the target from different positions of the captor in space. The spatial exteriority of the target is constituted by the possibility of freely and reversibly coming and going around it, alternately leaving and refinding contact with it. The target is localized in direction and depth when the rule governing pointing towards it is mastered. This is a good illustration of a 'law of sensori-motor contingency' [37]. Any given position of the target corresponds to a particular *sensori-motor invariant*, i.e. a *rule* relating sensory feedback to the actions performed; this rule itself is stable over and above the constantly varying actions and sensations. The whole interest of the minimalist approach is then to permit a precise characterization of this rule (on condition of simplifying the space of action to reduce it to two rotations, here the rotation of the arm around the shoulder and the hand around the wrist) (Fig. 4).

With this in place, the different conceptions of prosthetic perception (and indeed of perception in general) will depend on the way that these rules (the laws of sensori-motor contingency) are envisaged:

- either they are internal (inscribed in the central nervous system) and abstract (represented in symbolic fashion)—this is the representationalist view;
- or else they are external (determined by the objective structure of the layout) and embodied (directly related to proprioceptive information)—this is the enactivist view.

This question is particularly important for understanding the processes of the appropriation of devices for perceptual assistance.

3 Sensori-Motor Rules

In the first sort of approach, which is internalist, one might think that these rules correspond to an internal know-how, inscribed in the nervous system, constructed by association between the input sensations and information about the actions performed (this latter information could be based on proprioceptive signals and/or efferent copies of motor commands). However, a repetition of our experiments by Siegle and Warren [43] spreads fresh light on this question.

On the occasion of the same task of spatial localization, they separated the blindfolded subjects into two groups. In the first group, labelled 'Proximal attention', participants were explicitly instructed to attend to the location of the arm when the vibrating motor was active, and to consciously triangulate the location of the target by imagining their finger extending out into space. By contrast, in the second group labelled 'Distal attention', participants were explicitly told to not attend to their arms during the experiment, but to get an intuitive sense of the target's location and report how far away it felt. It was then observed that the instructions to attend to distal

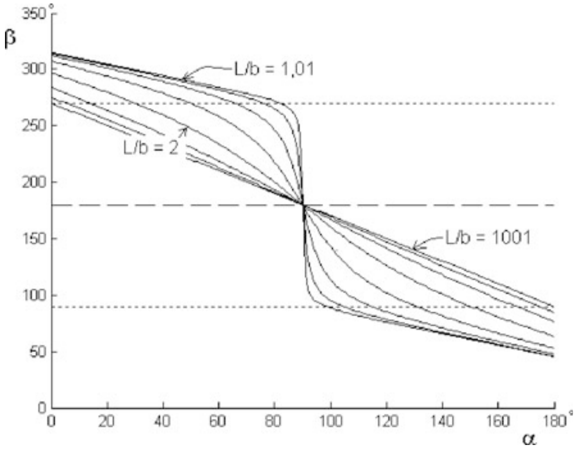

Fig. 4 *Curves* representing the relation between the angle of the hand with respect to the wrist (β), and the angle of the arm with respect to the shoulder (α), when the target is at different distances from the subject. These distance (L) are expressed in units of the length of the arm (b)

properties during learning resulted in improved performance and more precise judgments of target distance, whereas participants instructed to attend to proximal variables showed no improvement. In addition, Siegle and Warren [43] observed that the improved distance judgments were significantly correlated with increased perception of a solid object; that is, the less participants were paying attention to their arms, the lower the error in distance judgments, the more they felt a concrete solid object was really present before them in space. This supports the claim 'that improved distance judgments reflect a distal perceptual awareness rather than an explicit cognitive strategy' [43: 220]. Moreover this improvement is conserved even if one turns the seat on which the subject is placed through 90°, or one switches the photodiode from the dominant to the nondominant hand. Even if the actions to be performed, and thus the proprioceptive data are quite different, the subjects still appeared able to mobilize the results of their learning to localize the target. This is reminiscent of an observation already made by Paul Bach y Rita: subjects who were well trained with the TVSS held in the hand and a matrix of tactile stimulators placed on the back were quite able, without any additional training, to use miniature camera place on a pair of spectacles and a matrix of tactile stimulators placed on their chest [8].

These results militate both against an internalist representationalist account which supposes that distal spatial perceptions are deduced from proprioceptive data, and against an associative internalist account consisting of directly extracting regularities from the correlations between sensations and the movements performed. As Siegle and Warren [43] rightly note: 'transfer to the opposite arm changed not only the joint angles but the joints and muscles involved […]. These data clearly indicate that the emergence of distal awareness [cannot] depend on a particular set of arm configurations at a muscle- and joint-specific level' and so 'undermine a muscle- or joint-specific version of the sensori-motor hypothesis, and indeed any other hypothesis defined at the level of limb configurations'. Apparently, the only possible way to account for this data in the frame of the sensori-motor account is to postulate ‘a higher level sensori-motor contingency that is not joint-specific’.

In view of this, the question rebounds. What is the general structure of spatial perception that makes it possible to deduce in each situation the sensori-motor rule that applies? In the externalist perspective adopted by Siegle and Warren, which is close to the ecological theory of perception, it is posited that the gestures of pointing are determined in an allocentric reference frame, let us say the structure of the physical space of the layout. However, it is necessary to account for the transformations of lived experience that occur during the appropriation of technical devices for assisted perception. The sensori-motor rules depend as much on our possibilities for acting and feeling as on the concrete situation in which one is engaged [29]. It would rather seem, then, that perceptual learning leads to the discovery of the general organisation of the coupling between the subject and her environment, an organisation which makes it possible in each instance to master the rules of pointing towards objects.[3]

It therefore seems appropriate to adopt an externalist approach that we may call ’enactive’ in the sense that spatial perception is constituted in the sensori-motor relationship itself: it neither precedes nor follows this relation [31]. In order for the perceptual experience at time t to have a spatial content (i.e. for it to present objects located in an external space), the subject must indeed be actively engaged in this relation. The laws of sensori-motor contingency (relating the movement of the captor to the sensory input) are thus defined by the action capacities of the organism and the way in which these actions, depending on the structure of the environment, determine the sensory input. The lived body, transformed by the technical device which is associated with it, brings forth a specific domain of coupling with the environment. The laws of sensori-motor contingency are defined by the coupling device, the position of the target in the environment, and the action strategies of the subject. In order to give rise to a perception, a prosthetic device must be an instrument of coupling which modifies the lived body by defining new repertoires of action and sensation. The interest of this approach is that the organism itself does not need to have any explicit knowledge of the coupling device with which it is associated (the position and mode of action of the captors and sensory stimulators). It is sufficient for the subject to engage in a relation with the world, to progressively acquire a perceptual mastery [37]. This conception of active perception can be schematically illustrated as follows: (Fig. 5).

On this view, perception is not an internal representation, but the result of dynamic coupling between the organism and its environment. This is why we situate perception at the heart of the coupling, and not unilaterally within the

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[3] Incidentally, the concept of “pointing” used by Siegle and Warren actually presupposes already a spatial framework (if the subject thinks of her action in terms of the gesture of pointing in this or that direction, this means that she already has the experience of a space). This being so, the process whereby this framework is set up is precisely what we are trying to understand here: what is the process of setting up this framework which subsequently makes it possible to interpret gestures as gestures of pointing?

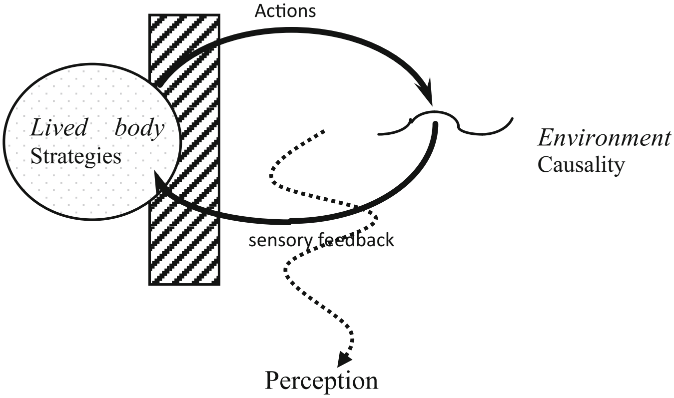

Fig. 5 Scheme of sensori-motor coupling. The system of prosthetic perception is a 'coupling device' which modifies the lived body by defining the repertoires of actions and sensations which are available to the subject. Via the environment, the actions 'a' give rise to sensory feedback 's': $s = g(a)$; concomitantly, the organism implements a strategy for generating its actions and modulating them as a function of its sensory feedback: $a = f(s)$

organism. It is easy to understand that in this conception of perception, there is an important distinction to be made between 'sensory input' and 'perception'. The 'sensory input' delivered to the organism is quite different from the full 'perception', which is based on the law defining the sensory feedback for a full range of performed actions.

4 The Space of Possibilities

If we come back to the general conception of space itself as a system of positions and possible movements, we see that the use of the device has transformed this system of possibilities. Of course blindfolded subjects, like persons who are blind from birth or through injury, do already have knowledge of the space which surrounds them and the actions which they can perform, even if it is only through the world of sound or the space of bodily action with tactile and kinaesthetic feedback. Nevertheless, with the radically novel mediation provided by the technical device a new space of possibilities is opened up, with a new form of perceptual presence of objects, this time in exteriority at a distance in a distal space.[4]

The preceding analysis now makes it possible to specify the way in which the space of possibilities is reconfigured on the occasion of this proximal-distal switch.

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[4] Epstein et al. (1986) have studied, in very controlled conditions, the question of the awareness of the existence of an external space through the use of a sensory substitution device—a question we considered again in Auvray et al. [1].

In the beginning, for the subject, blind or blindfolded, the field of possible perception (i.e. everything that the subject can apprehend by anticipation—eventually implicitly—as possibly being perceived by him) corresponds to the set of possible movements of the captor (here placed at the end of the finger) which explores the environment. In certain positions, the subject receives a tactile feedback that he can try to find again (this is not very difficult because the environment is immobile). But once the device is mastered, this field of possibilities is transformed and becomes the space of possible distal positions of the object. As for visual perception, the point of view, the position from which the object is perceived, is then spatially distinct from the distal position of the object.

The result of the instruction of distal attention in the experiment of Siegle and Warren seems to show that distal perception only occurs if the particular local actions are forgotten, relegated to oblivion, in favour of mastering the law of pointing towards the object. When attention is focused on the perception of an object, the stimulations delivered by the coupling device (be it natural or artificial) disappear from consciousness. Similarly, in natural vision, when we perceive a stable object at a certain distance in front of us, using our eyes and their movements, we have absolutely no consciousness either of the saccadic movements of our eyes, or of the variable sensory stimulations at the level of the retina [14]. What we are perceptually aware of is where the object is relative to us and where we are, as a point of view, relative to the object. Similarly here, there is only distal perception when one perceives the position of the object without paying attention either to the tactile stimulations, or to the variations in viewpoint which make it possible to determine this position.

In the case of proximal perception (we are considering here the case of tactile stimulation), there is spatial coincidence between the position of the perceived stimulation and the bodily position where the stimulation is received: for an 'object' occupying a given position, there is only one possible position of the captor, i.e. the position where the 'contact' occurs. By contrast, in the case of distal perception (in natural conditions of a visual or auditory type) there are an infinite number of possible positions of the captor for each position of the object (an object occupying a certain spatial position can be perceived from an infinite number of positions and orientations of the captor).

The nature of the switch from proximal to distal can thus be understood as a transformation of the sort of rule which relates the action to the sensory feedback. Whereas for proximal perception, the rule is that of identity between the position of the captor and that of the object, for distal perception this rule associates an infinite number of positions of the captor to each position of the object.[5] The duality between the particular fact and the general rule corresponds to the duality between

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[5] The notion of "distal" implies at the same time the idea of "aspect" and of "perspective" on the object: the distal perception of an object, precisely because of the possibility of having access to the latter from an infinity of possible positions, is the perception of the object "under a given aspect": the aspect that the object presents as "seen from here".

the position of the point of view and the position of the object. This duality is constitutive of distality.

The space of possible positions in play in distal perception is thus radically different from the corresponding space in the case of proximal perception. In the space of proximal perception, the relative positions of the perceived object and of the captor are of the same nature, and can be defined in the bodily framework of the perceiving subject. By contrast, in distal perception the relative positions of the perceived object and the captor are specified by *rules* of pointing (rules which indicate, for a given position of the captor, in which direction the latter should be oriented in order to establish a 'distal contact' with the object), and are thus of a different nature than the particular bodily positions which can satisfy these rules. They take the status of possible 'points of view', i.e. the site from which the object is perceived. Each position of the object in the distal space is specified by the rule which specifies the set of all possible viewpoints on the object. But at the same time, each of the positions of the viewpoint, rather than being defined within the bodily system, corresponds itself to a position in this distal space, and in principle could thus be specified by the rule giving the set of all possible viewpoints on it. The space of distal perception thus becomes a space of possible viewpoints.

5 Shape Recognition

Beyond simple spatial localization, we have seen that a device such as the TVSS can also give rise to the recognition of shapes of varying degrees of complexity. Here again, it is possible to adopt a minimalist approach in order to analyze with precision the mechanisms which make this sort of performance possible. We have developed another system with the aim of providing blind persons with access to digital forms present on a computer screen. The 'Tactos' system [26] consists essentially of a device for controlling tactile stimulators (Braille cells which electronically generate the movements of small pegs) as a function of the movements of a cursor on a computer screen (Fig. 6).

Typically, the cursor is a 4 × 4 matrix of 16 receptor fields (two pixels wide), corresponding to a surface of 64 pixels on the screen. When one of the receptor fields encounters at least one black pixel, this triggers the all-or-none activation of the corresponding peg on the Braille cell. The subject is blindfolded, and moves the cursor by means of an effector (mouse, stylus on a graphic tablet, touchpad….). The tactile stimulation is delivered to the *other*, free hand—but, as we will see, this does not hamper the perception of the forms. This device of perceptual supplementation thus allows for the exploration of a virtual tactile image.

For practical applications, it is possible to increase further the number of receptor fields and the corresponding tactile stimulators; but from the point of view of fundamental research it is actually more interesting to *reduce* the sensory information to the limiting case of a single stimulator corresponding to a single receptor field [50]. Even in this minimal version, we observe that subjects are able to

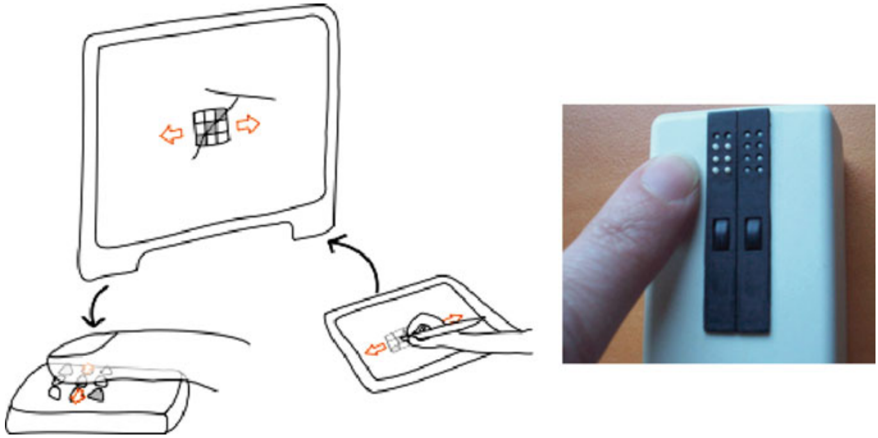

Fig. 6 **Tactos Device**. The pen on the tablet controls the movements of the cursor on the screen. The cursor corresponds here to a 3 × 3 matrix of receptor fields. When a receptor field covers a *black pixel* on the screen, the corresponding peg of an electronic Braille cell is activated. The picture on the right shows the two piezo-electric Braille cells combined to form a 4 × 4 matrix of 16 pegs

perceive forms [26]. These forms are not given to the sensory system as a complete two-dimensional pattern applied to the skin at each instant of time. When there is only a single receptor field, and thus a single sensation at each instant, there is again no intrinsic spatiality at the level of the input signal. If the subjects succeed in recognizing shapes in space—and they do—this can only be by virtue of an active exploration in the course of which they integrate their movements and the corresponding sensory feedbacks over time. Thus, by limiting the sensory input to just a single bit of information at each instant, we oblige the subjects to *deploy their perceptual activity in space and time*; and in this virtual reality situation it is then a simple matter to record and to analyze this activity. This is what we have called ‘perceptual trajectories’ (see Fig. 7) [30].

Here again and internalist perspective, in terms of the construction of a mental image by proprioceptive integration of the points of contact with the form, is quite impossible. The proprioceptive perception and memory of absolute position is too imprecise for the subject to be able to plot the positions of the hand which holds the effector (mouse, stylus…) in egocentric X-Y coordinates. It is thus quite impossible for the subject to scan the whole field of the screen, and to integrate the points of stimulation in order to construct a mental image of the form. In fact, if the subject inadvertently leaves the contour of the form she is immediately ‘lost’, and cannot even proprioceptively return to the last point of contact with the form.

Observation of the perceptual activity reveals some behavioural regularities. The subject starts out with large-scale exploratory movements, but as soon as she obtains a contact with a line, she converges to a *micro-sweeping* movement of small amplitude around the source of stimulation. This can be understood as essentially

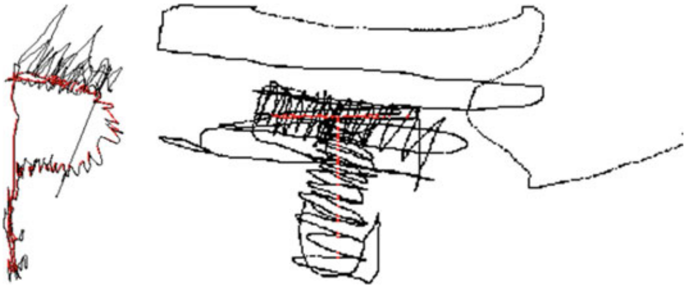

Fig. 7 Two examples of perceptual trajectories in Tactos

an operation of localization: the position of an immobile spatial singularity is *constituted* by a stable anticipation of the tactile stimulus according to the movements of the receptor field. The fact is that the imprecision and drift of the proprioceptive data do not allow their employment for a representation as an internal reconstruction of the form being explored (on the contrary, the proprioceptive system must be continually recalibrated by interactions with the environment). To the extent that there is no direct localization by proprioception in the absolute space of the graphic tablet, we have to admit that the subject's knowledge of her own position is indirect. The micro-sweeping movement enables the subject to identify her own position, not in absolute coordinates but relative to the form that she is exploring and perceiving. The subject situates herself in the allocentric reference frame of the figure she is actively exploring and perceiving: 'I am just a little to the right of the shape, that I just crossed, now I have come back to the left and I am pursuing it', etc. There is thus concomitantly localization of the singularity by oscillating movements, and localization of the movements of the receptor field relative to this singularity. At each instant, the subject situates herself relative to the shape that she is in the course of constituting. The 'viewpoint', i.e. the site from which the object is perceived, is not the finger under which the tactile stimulations are delivered, but the receptor field, because it is on the basis of this site that I define my actions. The place of perception (the cursor) corresponds to the point of action which is situated in the same space as the shape that is perceived.

At a higher level of organisation, the micro-sweeping movements around an initial point of contact are combined with a tangential displacement, following the local direction of the segment of the shape. This *contour following* is the realization of a second-order anticipation which bets on the stability of a temporal frequency of the sensations. However, if this strategy makes it possible to recognize straight or curved segments, it is not yet the recognition of more complex shapes such as letters. The latter only seems to be achieved when the subject is able to combine the gesture of micro-sweeping with a dynamic sequence of different segments which taken together reproduce the shape of the whole. When this is achieved, the receptor field traces the whole shape, with small oscillations and never losing contact.

We can appreciate here that perception is not the reception (and then the representation) of a shape, but rather its active construction. The trajectory is at one and the same time a *recognition* and a *constitution* of the shape. The categorization of perceptual data by integrating them into a known shape is realized by a gesture of *synthesis*. This gesture is like a scheme of construction of the shape, whereby the categories of the understanding apply to the data of sensorial intuition [27, 41]. Here the scheme of 'assimilation' corresponds to a concrete activity, deployed in the space of the movements of the subject. It is achieved by a 'gestural strategy' which produces, via the exteroceptive and proprioceptive sensory returns, a set of chained movements which make it possible at one and the same time to write the shape and to grasp it as a whole, in a single gesture of anticipation. Here, we can truly say that 'reading is writing'. This is indeed exactly what we do when we ask the subject to validate the perceived shape by drawing it free hand; in other words, to reproduce the gesture which directed her exploration. By studying the dynamics of the perceptual trajectories, we thus observe the concrete activity of the constitution of a shape in perception. We could hardly ask for a more telling example of perception as enaction—the bringing-forth of the perceived object—and not as 'representation'.

The perceptual modality instantiated by the Tactos system is indeed 'tactile'—for the reason that there is spatial coincidence between the receptor fields and the perceived shape. It is to be noted that this is independent of the fact that the sensory modality that is used is also that of touch. Indeed, in the case where there is only a single receptor field, it is quite possible to substitute the sensory return by a sound, or even by a flash of light. The perceptual activity would be exactly the same [18]. Thus, the perspective of perceptual supplementation leads us to put into question the classical definitions whereby the various perceptual modalities are *defined* solely by the sensory organ involved.

By reducing the sensory input to a single receptor field (just one bit of information at each instant), we have forced a spatial and temporal deployment of the perceptual activity, which has the advantage of facilitating its analysis. The tool functions here as a system for extracting operations which are habitually realized in the intimacy of the organism. Of course for practical applications there are advantages to restoring a degree of parallelism (with Tactos we routinely use a 4 × 4 matrix of 16 receptor fields, and in the initial version of the TVSS there were 400 receptor fields). When this is done, we observe an internalization of the perceptual activity: the economy of movement and memory allows for perception which is more rapid and more precise. What is to be noted, however, is that the parallelism of the captors is *formally equivalent* to a movement already performed between the diverse positions of the receptor fields [17, 44, 45]. This is similar to the situation of binocular vision: mobilizing two eyes and extracting the distance of the perceived object by their convergence is formally equivalent to using just one eye and a slight displacement of the head. Indeed this is what we do spontaneously to evaluate the respective positions of two objects by parallax, and this operation is equivalent to the triangulation that we studied in the previous section.

6 Technical Mediations of Perceptual Activity

We consider that the concepts developed above in the case of devices that are deliberately limited and simplified to the extreme can be generalized to the most varied systems of perceptual aids, in particular for better understanding the mechanisms of their appropriation.

6.1 Sensory Modalities and Perceptual Modalities

Following the analyses we have just proposed concerning the transformation of perceptual activity using technical devices, it appears that it is important to distinguish on one hand the ‘sensation’ (i.e. the sensory input delivered to the organism), and on the other hand the ‘perception’ which is specified by the rule which defines, for a given perceptual content, the sensory returns as a function of the actions performed. In completely analogous fashion, in the case of the use of a device for perceptual supplementation, it is important to distinguish on one hand the ‘sensory modality’ being used, which corresponds to the type of sensory input to the central nervous system; and on the other hand, the ‘perceptual modality’ which is defined by the sort of sensori-motor contingency law that the device gives access to. For example, for ‘The Voice’ [34] and the TVSS the sensory modalities that are mobilized are different, respectively auditory and tactile. Nevertheless, for The Voice as for the TVSS, one can say that the *perceptual* modality is basically of a visual type, since both these systems give access to the position and the shape of distant objects (by exploratory actions of translation and rotation). As noted by Grice [23], four criteria are generally used to distinguish between perceptual modalities: sensory organ, nature of the physical stimuli, properties being accessed, qualitative experience (see especially Auvray and Myin [3] for a discussion of the nature of the sensory-substituted experience in light of Grice’s analysis). O’Regan and Noë [37] add the criteria of sensori-motor equivalence, which refers to the type of sensory changes a given type of action produces. To this list, we propose to add the criterion of *proximal-distal organization*, which refers to the type of spatial and functional relations between the perceptual ‘point of view’ and the perceived object. The criterion of proximal-distal organization is of the same kind as the criteria of sensori-motor equivalence, but is focused on a different functional level and aims to account for *phenomenological* differences, more precisely differences in the *spatial content* of perceptual experience: how one situates oneself in space relative to the object being accessed perceptually, where one ‘feels’ oneself to be. Its leading principle concerns the functional difference between proximal and distal perceptual awareness: while *proximal perception* is characterized by the spatial coincidence between one’s ‘point of view’ and the perceived object (in order to perceive the object, one cannot do without being in contact with it), *distal perception* is characterized by a spatial noncoincidence between one’s ‘point of view’ and the perceived object: in order to perceive the object, one cannot avoid occupying a *different* position than the object itself. One noteworthy point is that whereas perceptual modalities can generally be classified as pertaining to one type or the other (distal or proximal), the sensory organ they normally make use of (eyes for vision, ears for audition, skin for touch, etc.) cannot: as demonstrated in an exemplary way by the TVSS case, the skin can be used to enact a distal-type perceptual awareness; conversely, one can make use of the eyes and ears to enact a proximal-type perceptual awareness.

The criterion of proximal-distal organization is especially useful to account for the technical diversity of prosthetic devices. For example, a perceptual modality of the visual type would be defined in purely functional terms as a situation where the point of perception (the point of view) is separate and at a distance from the perceived object. This would involve captors which specify infinite receptor fields, such that their movements are rotations and translations in the three dimensions of space. By contrast, 'touch' could be defined by the spatial coincidence of the site of perception (the receptor fields) and the perceived object. This would involve receptor fields with a finite dimension, and whose movements would be translation with respect to the object.

6.2 The Tool 'in Hand'

Whatever the system of perceptual aid, it is—like any tool which can be taken up in the hand—a device for artificial coupling between the organism and the environment to which it gives access. The new link which it creates, between the actions and the sensory returns delivered to the user, gives rise to the constitution of specific percepts. We find a common principle of functioning with the TVSS, the use of a computer mouse, games in virtual digital spaces, systems of tele-presence or virtual reality… In the case of the TVSS, the coupling between the actions (movements of the camera) and sensations (tactile stimuli) passes through the physical environment. By contrast, in the case of a computer mouse, the coupling between the actions (movements of the mouse) and sensory feedback (movements of the cursor on the computer screen) passes by a digital calculation. But in both cases, once the tool has been grasped and mastered, the tool itself disappears from consciousness in favour of the space of perception and action that it gives access to. The tactile stimuli on the skin and the camera in the hand are both forgotten in favour of the perception of an object 'out there' in a distal space; the computer screen and the movements of the mouse are forgotten in favour of the perception of the cursor and the operations that it makes it possible to perform in the digital space.

In these two examples, the technical mediation highlights features that are actually quite general in the use of tools of all sorts. When I grasp a stick in order to explore the surface of the ground, it is not the stick that I perceive as an object, but the bumps on the ground at the end of the stick. This has been well described by phenomenology: 'The stick of the blind person has ceased to be an object for him, it is no longer perceived as such, the end of the stick has been transformed into a sensitive zone, it augments the range and the scope of action of touch, it has become analogous to vision' [35]. In a similar vein, when I drive a car, I forget for the moment the vibrations of the steering-wheel and the seat, and instead I have the impression that I feel the gravel or the edge of the pavement under '*my* wheels'. These examples can be generalized to all the technical 'appendices' which transform our power of action.

The successful appropriation of a technical device occurs when the user 'becomes as one' with it. The device becomes invisible in the same way that our own body is invisible for use: we see neither our eyes, nor our optic nerves, nor our spectacles (if they are not too dirty!). One observes the same sort of result with other devices of sensory substitution such as the visual-to-auditory substitution systems the vOICe system [2, 3, 34] or the VIBE [25]. A coupling device which is properly appropriated becomes invisible precisely because it enables the subject to see. The invisibility of the lived body and of a tool that is grasped 'in hand' is explained by their constitutive role in perception. Participating in the constitution of the perceived object, they are no longer themselves the object of conscious experience. However, like all tools, they can also be 'put down', separated from the body and hence become again objects of perception. This reversible passage between the 'in hand' mode and the 'put-down' mode can of course be more or less convenient and rapid according to the device in question, from an implant to a pair of spectacles. In the case of the TVSS this passage can be rapid, the device being alternately considered as a perceived object (the blind person pays attention to the irritation produced by the tactile matrix on his skin) or invisible (when the blind person pays attention to the distal objects that the device enables him to constitute). Indeed it is often in this very interplay structured by the reversibility that a technical object takes on its meaning as such [32].

7 Conclusion: Perceptual Supplementation

In the light of these considerations, it seems that the denomination of systems of 'sensory substitution' to designate devices such as the TVSS of Paul Bach y Rita or the Voice of Peter Meijer is awkward and lacks generality. On one hand, we have seen that the conception and design of a system of perceptual aid should not only accomplish a transfer between different sensory modalities, but should also take into account the modes of action that it permits. If there is a 'substitution', it would be better to talk of 'sensori-motor' and not only 'sensory', because the relevant lived experience is not restricted to an analysis of the received sensation, but is rather produced by the complete dynamics of the sensori-motor coupling.

But on the other hand, is it even appropriate to talk of 'substitution'? Whatever the outcome of the debates about the nature of the perceptual experience procured by these devices, it must be recognized and admitted that it does not *replace* that of the absent modality; rather, it offers an original perceptual experience, specific to the repertoires of action and sensory return that are proposed by the device. In order to designate the whole set of devices which modify, enrich or transform perceptual activity, we propose to speak of *Perceptual supplementation* rather than 'sensory substitution'. Indeed, the term *supplementation* has the merit of expressing at one and the same time the act of compensating for a deficiency, and the act of positively expanding or increasing a capacity.

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Mobility Technologies for Visually Impaired People Through the Prism of Classic Theories of Perception

Marion Chottin

> *Where does the blind man's self begin? At the tip of the stick? At the handle of the stick? Or at some point halfway up the stick?*
>
> Gregory Bateson

1 Introduction

What, if anything, do the classic philosophies of perception have to tell us about technical objects, which, from the cane to more contemporary devices, aim to facilitate the mobility of the visually impaired? Is it possible that we should just leave these philosophies where we most often class them, that is, in a past synonymous with *passé*?

Far from the idea that philosophy in practice is removed from its history, here we propose a return to the thought that, in the seventeenth and eighteenth centuries, had taken perception as the focus of its investigation. We will forge the hypothesis that, for this reason, they can be of use in instructing the operation and use of mobility technologies—which are also the technologies of perception. Among these philosophies, the Cartesian theory of perception takes its place as seemingly the first to assert its presence in this domain. Descartes was, in effect, the first philosopher to have taken seriously an object that is still today that which the visually impaired turn to most frequently to assist their movement, and is an ancestor of today's Information and Communication Technologies (ICT): the cane, or what Descartes calls the "stick" of the blind.

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Certainly, Descartes carried out less theory on the cane itself than he did employ it to theorize (paradoxically) on visual perception. But this use is based on a conception of “stick” that here we propose to examine. For us, it will thus not be a question of examining his theory of vision through the prism of his figure of “the blind man with the stick”[1] , but to explain the manner in which he conceived of this figure, essentially independently from what he has written on vision. To do so, we will mobilize the corpus of Cartesian texts, which, although not required for the understanding of the theses on vision in the *Optics,* will enable the intelligibility of the “Cartesian theory of the cane”. With the help of these reflections, we will show that this also allows us to perform theory on the *operation* of more recent devices (I).

If Cartesian theory drafts a theory of their use, we will, however, state that on this point it falls short, and in no way nears completion. However, the problems encountered today by robotics engineers are not so much concerned with the operation (they know how to construct the devices they conceive of and design) than with the use of mobility technologies (how to construct tools that are relevant for the visually impaired). It is, therefore, necessary to mobilize one or two other theories. We will do so by appealing to empirical philosophies of perception, and, amongst them, that which seems to be the most consistent, and also the most relevant to consider that which Descartes has not theorized (i.e. the genesis of perception): Condillac’s ideas as presented in his *Treatise on the Sensations* (II).

Lastly, we will attempt to show where the interest lies in turning to Condillacian philosophy, since, in recent years, other theories have been mobilized and shown their fruitfulness in the understanding of mobility technologies—this is the case, for example, in phenomenology, and in particular, the philosophy of Merleau-Ponty.[2] Our question will thus be: what unique point of view does a Condillacian theory of perception enable for mobility technologies (III)?

2 Mobility Technologies Through the Prism of Descartes

2.1 *A Theory of the Cane of the Blind Man in Descartes’* Optics

Conceived of as application of the *Discourse on the Method,* this 1637 work contains a theory of vision, of its errors and means to correct them, in the aim of perfecting optical instruments (in particular, the telescope, invented shortly before), and mainly to avoid leaving their fabrication dependent on the chance of circumstances. From the very opening of the work, Descartes indicates that he will not

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[1] On this point, see Marion [7, 28] and Le Ru [26]. On the topic of the Cartesian use of the figure of the blind man with the stick for thinking more generally on the transmission of movement, see Le Ru [27].

[2] See notably Lenay et al. [25].

seek to determinate the nature of light, but will mobilize “two or three comparisons” (p. 152) to render the way in which it causes vision intelligible. The figure of the blind man with the stick constitutes one of these comparisons. And when Descartes notes, about those born blind that employ the use of a cane, “that one might almost say that they see with their hands (…)” (p. 153), what does this mean to say?

For Descartes this signifies that the blind man’s cane is not the equivalent of a tactile organ, an extension of the arm and ordinary sense of touch, characterized by direct contact with the perceived object. It is thus not an extended arm, but a medium. It is not any more, however, the equivalent of the organ of sight. In other words, the blind man who perceives by means of his stick does not *see* any object. For Descartes, the cane is not a substitution for miracles, or for scientific processes: it does not give vision to the visually impaired. Just as he indicated in *Discourse on the Method*, that we can, through knowledge, “make ourselves, *as it were*, the lords and masters of nature (p. 142–143, our emphasis), to point out that we will never be as God is, here he writes about blind men with sticks “that one might *almost* say that they see with their hands”, to signify that it is a question of something other than vision. For Descartes there exist “qualities” belonging properly to the sense of sight (light and colours), that is to say, sensible qualities that, without determining any essence, only belong to that sense, and to which the cane, evidently, does not provide access. Based on a clear distinction of sight and touch, such a refusal to say that the cane allows one to see, or to make of the cane an equivalent of the eye, is essential for knowledge on blindness. On the contrary, reducing the differences between the senses can lead to minimizing the loss that it causes.

If the cane is neither the equivalent of the hands, nor the eyes, it enables an “almost vision” in the sense that, at the same time similar to, and different from, sight, it allows a perception in which objects are apprehended not only externally, but above all, at a certain distance from the body. In short, the cane opens onto a perceptual mode that blends the properties of touch (tactile sensations experienced via the stick) with at least one essential feature of sight (perception of distance). A detour by the critique that Merleau-Ponty employs to counter the Cartesian theory of perception will aid in our precision on this point.

Merleau-Ponty, the author of *Eye and Mind,* recalls that, for Descartes, “the blind (…) ‘see with their hands’” (p. 131). If he does not take into account the “almost”, it is not to falsely attribute to Descartes the thesis according to which the cane would substitute for the absence of eyes, but on the contrary, it is to reproach him for having conceived of vision on the model of touch: Merleau-Ponty’s assessment is that if Descartes attributes a “vision” to the blind man with the stick (a vision that is, in fact, reduced to touch), it is that he had already conceived of vision as a tactile organ[3] . In other words, for Merleau-Ponty, if Descartes’ cane elicits an “almost vision” it is for the sole reason that vision itself is “almost touch”. However, this reading does not seem to us to be precisely faithful to the text of the *Optics*.

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[3] Merleau–Ponty writes: “The Cartesian model of vision is modelled after the sense of touch” (ibid.). This reading is also that of M. Serres, but rejected by Cavaillé. Cf. [7, 34].

Certainly, Descartes estimates that vision is realized through the rays of light that hit the retina, like the stick in the hand of the blind man. But he knows perfectly well that these rays, unlike the stick, are not themselves felt, and makes recourse specifically to this comparison to make perceptible, and thereby intelligible, the trajectory of light to the eye. Let us not forget that "*comparaison n'est pas raison*". In addition, for Descartes, the identification of the role that rays of light play in the production of vision is a refutation of the classic theory that material images detach from things to form an impression on the retina—a theory which, however, conceives of sight as touch. A reading of Merleau-Ponty confirms, that by its very limits it cannot be a question of reducing the perceptions elicited by the stick of the Cartesian blind man to ordinary tactile perceptions. In this regard, what follows in the *Optics* would be lacking in ambiguity: according to Descartes, "one might almost say (…) that *their stick is the organ of some sixth sense given to them in place of sight*" (p. 153, our emphasis). This statement, which seems to be decisive, must also be read in light of its "almost". Firstly, a stick is not an organ. If, for Descartes, "so all that is artificial is withal natural [21, p. 289], in the sense that the laws of mechanics are the same as those of physics, the ontological difference between human productions and divine works could not be denied. Furthermore, no external will has governed the use of the cane by the blind and the visually impaired. No divinity has offered them sticks to compensate them for their loss of sight, as Zeus has given the gift of divination to Tiresias to compensate for the blindness inflicted on him by Hera. However, because the perceptions that the cane enables are not, strictly speaking, visual, nor reducible to that of ordinary touch, it is legitimate to attribute them to "some sixth sense", which, without invoking a divine gift, is indeed present in the blind.

But what Merleau-Ponty has especially in his sights, and what he refutes, is the idea that these perceptions would result from a judgement based on the (first) sensations provided by the stick. The "almost vision" occasioned by the blind man's cane, as elsewhere in common perception, and which serves as a model in the *Optics*, would be nothing but an intellection[4]—a thesis which would come to lack in the essential dimension of *sense* perception. This is why Merleau-Ponty judges that, according to Descartes, the stick of the blind man is in no way an organ, and can be reduced to a simple instrument: in the *Optics*, the blind man manipulates his stick as he already manipulates his bodily machine.

However, when he employs this figure of the blind man with the stick further on, Descartes insists precisely on the fact that he perceives without "in any way knowing" or even "thinking" of the position of his hands:

> (…) when the blind man (…) turns is hand A towards E, or again his hand C towards E, the nerves embedded in that hand cause a certain change in his brain, and through this change his soul can know not only the place A or C but also all the other places located on the straight line AE or CE; in this way his soul can turn its attention to the objects B and D, and

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[4] Cf. Merleau–Ponty, ibid., p. 136 : "(…) the vision upon which I reflect ; I cannot think it except *as* thought, the mind's inspection, judgment (…)".

> determine the places they occupy without *in any way knowing or thinking of those which his hands occupy*. (p. 169, our emphasis)

Figure in the *Optics,* p. 135

Thus, a blind man perceives, through the means of one or two sticks, the relative placement of objects, because the nerves of his body transmit the information to the brain—and not because it performs a calculation (or even a reasoning) from the sensations that he feels in his hands.[5] According to Descartes, the blind man has the ability to perceive not only the end of the stick that he holds in his hand but yet, via an act of attention, the objects in contact with the opposite part, without the latter perception presupposing the first as a conscious condition of possibility. In sum, the stick (or cane) is not uniquely, for the Cartesian blind man, *what he perceives*, but before all *that with which he perceives*—that is to say, it constitutes the equivalent of an organ.[6] Therefore, when Merleau-Ponty writes that "our instruments (…) are added-on organs" (ibid., p. 138), he says nothing other than what his predecessor has already stated.

What is thus realized, through Descartes' pen, is an upheaval of the traditional division of sense perception into five types, based, paradoxically, on a traditional conception of the distinction of five senses[7] : The site of a veritable sixth sense, the cane places the blind man in a new perceptual universe. This is an important point, and reinforces the idea of Charles Lenay and François-David Sebbah that contemporary devices should not be called sensory "substitution" but "supplement" because they achieve "the opening of a new space of coupling of a man with the world" [our translation, 25, p. 58]. Thus, the cane can justly be classified as the

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[5] On this point, we thus join Alquié [1, p. 429], for whom the "natural geometry" evoked by Descartes about the blind man with the stick is neither a conscious nor unconscious calculation, but a "mysterious effect by which the bodily dispositions give sense-experience and knowledge to the soul what it must sense and know" (our translation). Quoted in Cavaillé [7, p. 117].

[6] This is also how J.-P. Cavaillé assesses these pages of the *Optics* [7, pp. 62–65].

[7] Cf. the *Description on the human body*, in which Descartes treats the operation of the five senses one after the other, and explains the differences in sensations they occasion by the specificity of nerves that constitute them.

ancestor of such devices.[8] We will now show how, far from a refutation of, these new devices are conceivable within the Cartesian theory.

2.2 Information and Communication Technologies Through the Prism of Descartes

It is sometimes expressed in the literature that these apparatuses come to refute the Cartesian theory of perception. In fact, ICT could indeed help to reveal two things. Firstly, that perception arises from learning (as Descartes would support an *instantaneist* conception of perception); and secondly, that perception involves the movement of the body itself (where Descartes would reduce it to an act of the mind).

Indeed, what we generally consider to be the first mobility ICT, i.e. the "Tactile Vision Substitution System", developed by Bach-y-Rita in the 1960s, shows that time and perception are two necessary conditions for the occurrence of perceptions that it enables. Remember that the TVSS is a device comprised of a camera that records the images of the exterior world and an instrument that allows it to transform these images into electric data, retransmitted afterwards onto a part of the skin of the subject (that of the back or chest, and today, the tongue). The operation of the apparatus involves the action of the body: to perceive a particular object, the individuals endowed with this device must move the camera from right to left, up and down, and also zoom in and zoom out.[9] The experimental phase of the device also shows that these individuals must repeat these gestures multiple times, to finally reach the identification and localization of what is an obstacle, a man, etc.[10]

Conversely, the Cartesian theory would not tie in perception, temporality or bodily activity. And indeed, it has never placed these parameters at the heart of the perceptual process. According to this theory, perceptions arise from the transformation of the movement of nerves occasioned by these objects into sensations of the soul, by virtue of laws instituted by God, whose efficiency rests on the principles of geometry, through an almost instantaneous process. In the first instance, light, for Descartes (although we are now aware that he was mistaken), spends no time in passing from the luminous object to our eyes:

> In the first place this [*sc*. the comparison to the blind man with the stick] will prevent you from finding it strange that this light can extend its rays instantaneously from the sun to us. For you know that the action by which we move one end of a stick must pass instantaneously to the other end, and that the action of light would have to pass from the heavens to

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[8] The fact that state-of-the-art canes exist today gives confirmation on this point, Cf. Pissaloux and Velazquez [32].

[9] Cf. Bach-y-Rita [3], Declerck et al. [14, p. 253].

[10] Ibid.

> the earth in the same way, even though the distance in this case is much greater than that between the ends of a stick. (*Optics*, p. 153)

The blind man apprehends objects as soon as his stick touches them: also he may be certain, if not of their essence, at least of their existence—in contrast to those possessing normal sight who, shortly after Descartes' death, were aware that it was possible to see dead stars and that all visual perception only accessed the past. Did visually impaired people live in another temporality than those who privilege sight over the other senses? But let us push forward. Secondly, the impression (instantaneously) left by the object on the sense organ is yet, according to Descartes, transmitted *instantly* to the site in the brain where it is transformed into sensation[11]—and this, because the nerves connecting the eye to common sense form a continuum that may not be moved at one point without doing so at all of the others. The last phase of this process is trickier to interpret: are cerebral movements transformed instantly into sensations? Coming back to the text of the *Optics* as cited above, we can state that, for Descartes, visual perception of the position of objects rests, at the very least, on the movement of the eyes. In other words, and as we have shown elsewhere,[12] the laws instituted by God work upon a body in movement and are thereby inscribed in time.

However, to recognize that the body, in Descartes, is involved in the emergence of perception is not to make "the blind person with TVSS" a Cartesian figure: for the author of the *Optics*, perception requires no reiteration, no repeat of the experience. As soon as the body moves, the soul is aroused, invoking the efficiency of divine laws, which exempts the subject from mobilizing allegedly innate geometric ideas. This is why we have elsewhere classified the Cartesian device as a "*fixisme sensori-perceptif*",[13] despite the concepts of time and action that it implicitly mobilizes. Can we say, in this case, that ICT contradicts the Cartesian theory?

From a Cartesian point of view, these devices do not arise out of the divinely instituted one that occasions perception: there are no natural laws by virtue of which tactile stimuli (such as electric stimulations that are apprehended on the skin) are transformed into objects perceived at a distance from the body itself. In this framework, the time required for the visually impaired to perceive through TVSS is a sign of the artificial character of these perceptions, and not a proof of an essential temporality in perceptive phenomena. However, if he maintains that perception, such as it results from divine laws, does not reveal any genesis, Descartes never maintained that it do not when it is the site of new perceptual modes—such as that which, according to him, the blind man experiences with his stick. Much to the contrary, the philosopher estimates that the blind man must learn to perceive with his stick to, by virtue of it, apprehend objects:

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[11] Cf. *Rules for the Direction of the Mind*, Rule XII.

[12] Cf. [11], the chapter entitled "Le surgissement temporel de la sensation".

[13] Ibid.

> It is true that this kind of sensation is somewhat confused and obscure in those who do not have long practice with it. But consider it in those born blind, who have made use of it all their lives: with them, you will find, it is so perfect and so exact that one might almost say that they see with their hands (…) (*Optics*, p. 153).

In this case of exceeding natural sensibilities (which, according to Descartes, is an innate sensibility), the repetition of experience is necessary for perception, because it is required for the becoming-organ of the stick: the practice of manipulating a cane does not at first present gains in skilful and precise movement, but before all it incorporates an artifact, augments the body itself. Thus, Descartes conceives that there exist perceptual modes that are beyond those that were traditionally identified, and assessed that these modes are but the object of a genesis based on bodily movement: time and action find themselves as necessary conditions of perception. It is in this sense that, according to us, ICT does not contradict the Cartesian theory of perception, but are conceivable within its framework.

Moreover, Descartes provides the condition of possibility and the principle of this circumscribed perceptual learning—which, in this sense, is not only conceivable but conceived of by Cartesian theory. To understand this point, let us first turn to *Treatise on Light,* and in particular this passage:

> (…) if words, which signify nothing except by human convention, suffice to make us think of things to which they bear no resemblance, then why could nature not also have established some sign which would make us have the sensation of light, even if the sign contained nothing in itself which is similar to this sensation? Is it not thus that nature has established laughter and tears, to make us read joy and sadness on the faces of men? (p. 81)

These lines teach us that there is nothing unintelligible in the transformation of bodily movements into sensations of the soul, since we conceive of this passage, evidently based on non-resemblance, on the model of human language: if men were able to establish signs that refer to things without in any way resembling them, then God was *a fortiori* able to make it so that an alteration of the material signifies an alteration of the immaterial. The possibility of this institution is supported by the sure existence of another divine language: that of the passions, which we speak naturally. Similarly, there should be a language of perceptions, operating innately within us. However, if here we substantiated in the idea that divine laws of perception operate "in us" and "without us"[14] , are we not here diametrically opposed to perceptual learning?

Not if we consider this thesis on the institution of nature as at the same time susceptible to give reflection on its own surpassing:

> It is useful to note here (…), that although nature seems to have joined every movement of the gland to certain of our thoughts from the beginning of our life, yet we may join them to others through habit. Experience shows this in the case of language. Words produce in the gland movements which are ordained by nature to represent to the soul only the sounds of their syllables when they are spoken or the shape of their letters when they are written, but nevertheless, through the habit we have acquired of thinking of what they mean when we

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[14] But not "despite us" as found in other natural judgements in Malebranche.

> hear the sounds or see the letters, these movements usually make us conceive this meaning rather than the shape of the letters or the sound of the syllables (*The Passions of the Soul*, p. 348)

Whereas the *Treatise on Light* makes human language a reason *a fortiori* in favour of the existence of a divine institution of perception, these lines mobilize it in an almost-opposite direction, to support the possibility offered to man to bypass the laws of God. Thus, human language is not only an institution analogous to that of perception; it rests on a sensory transformation of it: for words to signify things, bodily movements must, by nature, signify such or such sound, and need to refer back, *beyond these sensations*, to the things that men have decided to attach to these sounds—without which words for us would be reduced into their simple material sonority, as they do, for Descartes, in animals. Thus, human language to him testifies on its own the possibility of an alteration of divinely instituted laws. In an act that, in a way, thumbs his nose at God, he alters the union of the soul and the body, which, as the occasional cause of a solitary thought, has become a condition of intersubjectivity. This is what informs the apprehension of artificial perceptions.

The blind man can perceive objects with his stick because it is possible for a man to alter in time the laws of the union—in this case, to arrange it so that the movements imprinted on his hands by the cane become signs, not only of certain manual perception but yet new perceptions of sensible objects. This phenomenon of bypassing, or at least a new “coding”[15] of the laws of the union, sheds light on the operation of TVSS. It is also quite remarkable that Bach-y-Rita reappropriates the linguistic conception inherited from Descartes, based on the (anti-Keplerian) thesis that there is no homogeneity between the strictly optical phase of vision (the impression of luminous rays on the bottom of the eyes), and the following, purely mechanical one (from the optic nerve to the brain):

> In normal sight, the optical image does not get beyond the retina. From the retina to the central perceptual structures, the image, now transformed into nerves pulses, is carried over nerves fibers. It is in the central nervous system that pulse coded-information is transformed into the subjective visual experience. (2002, p. 497)

We will thereby not be surprised to read, a bit further on (p. 511), from the pen of Bach-y-Rita, the very expression “bypass”, mobilized to qualify the cerebral effect of the use of sign language by deaf people—language perfectly analogous, according to the author, to his TVSS. However, what follows is as if he were drawing a non-Cartesian conclusion from Descartes’ own theory. Since they are movements of the nerves, and not the retinal image itself, which are transmitted to the brain, it seems possible, according to Bach-y-Rita, “for the same subjective experience that is produced by a visual image on the retina to be produced by an optical image captured by an artificial eye (a TV camera), when a way is found to deliver the image from the camera to a sensory system that can carry it to the brain” (p. 497). In short, the exclusively mechanical dimension of the second phase of the

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[15] According to the now adopted formula from Marion [28, p. 254].

process makes the retinal image superfluous to vision and opens up the possibility of substitution for any other image, provided that it can agitate certain nerves and convey movements to the brain. Thus, for Bach-y-Rita, the TVSS is a genuinely substitute, and not just supplementary, sensorial system: ideally, if not in reality, blind people who are so equipped are likely to *see*[16]. By all appearances, it is a matter, according to him, of a direct implication of perceptual semiotism.

We have nevertheless shown that, according to Descartes, the blind man with the stick does not, strictly speaking, *see,* but accesses a new perceptual mode. While it is true that under the Cartesian theory of natural perception, any individual whose nervous system is not compromised is capable of seeing (what recent experiences seem to have confirmed[17]): a blind person in whom we successfully stimulate the nervous movements that operate in vision would be, literally, a blind (*ab-oculis*: "without eyes") sighted person—and this, even if they had no retina (which science, however, has not yet shown), because, for Descartes (as for Bach-y-Rita), it is not the retinal image that constitutes the proximate cause of vision, but the nervous impulses in the brain. The author of the *Optics* even highlights that this possibility in fact partially realized in "madmen" and "those who are asleep" (*Optics*, p. 172). However, the perceptions evoked by the cane do not obey, for Descartes, the same explanatory schema: if he attributes no veritable vision to the blind man with the stick, but only an "almost vision", it is because he assesses, logically, that the nerves agitated by the movements of his hand are those that evoke, in the brain, tactile perceptions, and not visual ones. It would undoubtedly be the same for the blind person with TVSS, insofar as Descartes sees it, each sense corresponds to a series of nerves and where the organ solicited in this case is that of touch (the skin of the back, chest, abdomen or tongue). For Bach-y-Rita, on the contrary, any device by which an image is "coded" into nerve impulses is equally able, by virtue of brain plasticity, to evoke visual perceptions. In short, the latter considers that a kind of perception does not depend on the organ invoked but on the type of stimuli caused. Descartes would most likely consider that Bach-y-Rita remains a prisoner of the traditional significance given to the image: for the philosopher, it is not only the retinal image that is superfluous to vision, but any physical image, whatever it may be. However, according to him, we would never produce visual images by activating any nerves other than those that God had allocated to vision. Man, for Descartes, is able to modify the ways of God and produce new perceptual modes, but cannot reproduce those of divine laws without respecting their *modus operandi*. If one wants to give sight to the blind, it is thus useless to conceive of supplementary (or substitute) sensory systems. Only retinal prostheses are capable of doing so. But if one intends to increase their mobility, and open them up to, as well

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[16] The researcher thus estimates that a kind of sensations is not determined by the organ they issue from, nor by the subjective experience of the subject that receives them but by the type of stimulus that occasions them.

[17] Cf. Reich et al. [33].

as the clear-sighted, new perceptual fields, then, indeed, these systems offer the most interest in this regard.

Thus, Cartesian philosophy teaches us that it is not necessary to conceive of perception as an effect of the body and of time to consider how assistive technologies operate. It suffices to have a theory of the production of natural perception, which lends itself to thinking, differentially, about that of artificial perception, and what can be transposed onto these devices: this is the case of Descartes' theory, which makes perception as exercised via the five senses an effect of the divine laws of the union of the soul and the body, and, consequently, of mediated perception the effect of a bypassing, or temporal reconfiguration of these laws—and not, as one might think at first, the result of an augmentation of the bodily machine by adding a second mechanism, and the soul's reasoning over the combined data from this new artifact. For Descartes, let us not forget "that I am not only present in my body as a sailor is present in a ship, but that I am very closely joined and, as it were, intermingled with it, so that I and the body form a unit" (1641, p. 56).

The Cartesian theory also provides the principle of the use of ICT: it is a matter, for the individuals fitted with these units to indicate to internal movements within their bodies other perceptions than those that these movements naturally signify, and, thus, to access new perceptual worlds. However, nowhere does Descartes describe the way in such learning would effectively be realized—which is, however, a necessity for one who wishes to philosophize on these technologies. This is the reason for which we must now turn towards another theory.

3 An Alternative Theory: Condillac's *Treatise on the Sensations*

3.1 From a Causalist Theory to an Empiricist Theory of Perception

Far from simply "adding" Condillac's theory to Descartes', we will somewhat substitute the Condillacian theory of perception, as presented in the *Treatise on the Sensations* (1754), for the Cartesian theory of the *Optics* and of the *Passions*—and we will do so because thought on perceptual learning assumes the transition to a new theoretical framework.

Does this transition, as Merleau-Ponty believes, involve a departure from the external point of view (or the status of the exterior observer) that Descartes would adopt on perception, in favour of an internal point of view, that of the perceiving philosopher? For the author of *Eye and Mind*, Descartes places himself to the exterior of the perceptual act, and thus condemns himself to employing a "thought of seeing" instead of seizing the "vision in act" (p. 136). Descartes examines at the eye as it sees, the blind man as he touches with his stick, and from there reconstitutes the perceptual act. According to Merleau-Ponty, Descartes does not perceive, but thinks of perception, and reduces it to a “mind’s inspection” (p. 136).

Descartes does, in fact, come to adopt, in the *Optics*, such a perceptual externalism—as the only engraving in the work attests:

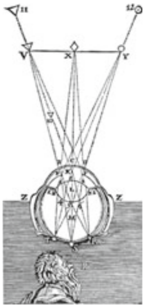

Figure in the *Optics,* p. 139

However, the external point of view on perception is condemned in effect to miss all, or at least part of, the genesis of perception: if in accordance with the scientific position on nature, such a point of view makes the explanation of vision possible, i.e. the demonstration of its causes (from the object to the movements that affect the brain), as far they are—as the body they affect—of a material nature, and thus able to be seized from the outside (in third person), this perspective does not allow the apprehension of perception in itself, that is to say, as a mode of thought. This is why Bach-y-Rita, in describing the way in which his subjects learn to perceive with TVSS, is forced to rely on their testimony, and, without it, could not know that, for example, “exploring the face of one’s loved-one can be very disappointing, since the emotional messages (…) have not been perceived with our TVSS” [3], p. 500).

Nevertheless, if it is true that perceptual learning, as perception itself, cannot be truly apprehended from the exterior, it is not the case that Descartes set forth a purely externalist theory. First of all, he is well positioned to say that thought is experienced in the first person,[18] and to make of perception a mode of thought.[19] How, under this framework, could he judge that perception is accessible from the exterior? We should not confuse the input of causes, which, for Descartes, can and must pass, at least in part by observation (he takes the example of the eye of a bull) and the apprehension of perception in itself, or of the perceptual act, impervious for its part to external scrutiny, whether of the senses or of the intellect. This definition of thought through the consciousness that we have of our objects of thought is elsewhere at the very foundations of *Meditations on First Philosophy*, in which, as we are well aware, Descartes expresses himself in the first person and analyzes the

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[18] Descartes [21, p. 113]: “*Thought*. I use this term to include everything that is within us in such a way that we are immediately aware of it”.

[19] Descartes [23, art. XVII].

content of his mind. Without a doubt, if he takes his own perceptions as an object in this text, it is just as much to place the sensory world aside, and to come to back to it at the end as a world that we deduce, with little or nothing to say about the world that we perceive. Between the two, the subject is no longer, or does not believe himself to be anymore than a thinking (meditating) subject. It was as if Descartes assumed the point of view of the perceiving subject for the sole purpose, which he deems necessary for the foundation of knowledge, of disqualifying sense perception.

In the *Optics*, on the other hand, Descartes happens not only to adopt such an internal point of view on sense perception, but judges it fertile for knowledge. Here indeed is what he writes, just before introducing the figure of the blind man with the stick:

> No doubt you have had the experience of walking at night over rough ground without a light, and finding it necessary to use a stick in order to guide yourself. You may then been able to notice that by means of this stick you could feel the various objects situated around you, and that you could even tell whether they were trees or stones or sand or water or grass or mud or any other such thing. (p. 153)

Here, Descartes indeed recalls an experience, in the first person, which should have been, in his time, relatively common, and implicitly asks each reader to reproduce it in thought. And Descartes thus describes the effects of this “sixth sense”, much more highly developed in those blind from birth than in the sighted. However, the transition from the experience of darkness to that of blindness does not constitute, along these lines, a change in the point of view adopted on perception. If, in fact, Descartes then goes on to observe a blind man who manipulates his stick, it is because he has started to adopt, in thought, the point of view of this blind man. If this was not the case, how could he write that the blind man perceives differences “between trees, rocks, water and similar things by means of his stick” (p. 153)? From the exterior, all that is possible to say is that an individual moves around, and touches objects with his stick. This figure of the blind man thus does not constitute as much the object of a sensory observation, than the effect of a thought experiment. Which is to say that Descartes had the good angle to describe how perceptions occasioned by the cane are learnt. We must, therefore, look elsewhere for the reasons why he did not.

If he said nothing about the way in which the blind man learnt how to perceive with the stick it is, firstly, that such a discourse would have weakened his theory on natural perception, based on the idea of divine institution. A genetic analysis of the manipulation of the stick would have given the impression that ordinary perception was in itself a genesis, and encourage doubt over the effectiveness of divine laws. According to Descartes, only the experienced blind man comes to instruct a theory of vision, not the one that learns to see.[20]

But if the author of the *Optics* does not theorize on learning how to manipulate the cane, it is mainly that he was not in a position to do it more—not due to the

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[20] Cf. Chottin [10].

point of view that he adopts on perception, but in the use that he makes of this point of view. We know that Descartes considers the figure of the blind man with the stick as a comparison through which it is possible to represent the mechanical causality of natural perception: far from being provoked by fleeting images, vision requires nothing more than a series of movements that take place one by one. However, these movements are not sensed by the perceiving subject—this is also why Descartes makes recourse to the comparison with the blind, as we have stated above. However, we have shown that perceptual learning, according to the author of *Passions*, consists of a reconfiguration of divine laws that associate, like in language, certain movements with certain sensations of the soul. But how is one to establish a language from movements of which we have neither knowledge, nor consciousness? While the Cartesian conception of the cane relative to its becoming-organ, as well as his theory of natural perception, seem to evade Merleau-Pontian objections, that of its use reveals itself to be more permeable to his critique: if we understand that divine institution may happen, or rather permits the subject to dispense with paying attention to the movements of his brain, it is much harder to seize how man could give meaning to these movements as original perceptions without knowing their nature, or even, in most cases, their existence. However, such involvement seems required: how can we think about an institution without the subject that institutes it[21] ? We will finally highlight a last difficulty inherent to the Cartesian semiotism: if perception is analogous to language instituted by men, is it not the mental or imaginative representations—and not the sensory—that the perceiving subject must attain, as he does for ideas, through words? Do not these theoretical difficulties signify that we need to step beyond perceptive semiotism? The theory of the use of the cane, but also of TVSS, evidently assumes employing the point of view that Descartes took on perception differently—to interpret it as the means of attaining not the unperceived causes of perception, but the very phenomenon itself.

Lastly, Descartes' error did not consist of taking a wrong position on perception, but of attributing to it an inadequate finality. This is at least what numerous empiricists of the eighteenth century believe, who for the most part acclaim Descartes as a philosopher of subjective analysis but reproach him as having gone beyond experience and supported arbitrary theses. It is a question for those such as Locke, Berkeley, Diderot, Condillac, Hume, etc. of not extracting from experience truths over perceptual causality, and of relying on the facts that the subject apprehends of his consciousness.

Before being practiced by phenomenology, suspending consideration of the production of perceptions had thus been the case for a certain number of Descartes' successors. Among them, Condillac presented the theory that, to us, seems to have the most to add to help us make sense of mobility technologies. Indeed, from his

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[21] The problem seems to come from the fact that, according to the Cartesian theory of perceptual learning, these are not natural perceptions, entirely conscious, which allow the attainment of artificial perceptions, but only the cerebral movements, which are unperceived.

Essay on the origin of human knowledge (1746), the genesis of perception is taken as the very object of his philosophical enquiry. As for Descartes before him, for Condillac it is a matter of analyzing the mind—but not by way of methodical doubt, deemed ineffective—and the subsequent elimination of the sensed world. Instead, it is a question of maintaining perceptual consciousness and reflecting on perception through the abstraction made over physical movements that can (or not) produce it[22] . We thus discover its series of transformations and the ideas its generates: precisely what we were lacking in Descartes. It is, however, on *Treatise on the Sensations* that we will focus, because in this text Condillac mobilizes the figure of the blind man with the stick and reimagines it, at the heart of a radicalized theory of the genesis of perception.

Far from describing his perceptions, Condillac imagines, in this new work "a statue internally organized like ourselves, and animated by a mind deprived of any kind of idea. (…) Its marble exterior did not allow it the use of any of its senses, and we reserved for ourselves the freedom to open them at will to the different impressions they are susceptible of" (p. 170). Why such a device? If it is, for him, a matter of taking perception (and not its causes) as his object, does not the abbé then fall into the trap of the method attributed (in part falsely) to Descartes, which involves taking an external point of view on perception, and, moreover, a totally fictive one?

Rather, his approach consists of somewhat of an extension of what we saw at work in the *Optics*: since it is true that, throughout the work, Condillac observes the statue from the exterior, it is not that he had arbitrarily placed certain perceptions in its mind, but that he had first put himself in its place,[23] to then re-transcribe his experiences through a thought experiment fuelled by the knowledge of his time. But one question remains: why, on one hand, does he start by denying the statue the faculties (attention, judgement, reflection, etc.) that characterize the human mind, and, on the other, attribute the senses to it one after the other, while human perception presents itself from the outset as multisensory? In short, how could such a device instruct the use of mobility technologies that are evidently not designed for statues without ideas?

For Condillac, to depart from the perception of man "normally" constituted, as he does in his *Essay*, amounts to distorting the genesis of perception, that is, to tend towards to conferring on one sense that which arises out of another—primarily, to attribute to sight the perception of the external world, when according to him, it arises from touch. Although it requires analysis, the perception of space *without sight* is not problematic in itself, opposite to the perception of space *through* sight; due to the fact the eyes alone give no idea about the object external to the mind. Regarding the first abstraction he makes of the faculties, Condillac justifies it, like in the *Essay*, by his plan to produce the genesis. This device allows him to establish

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[22] Ibid., p. 30.

[23] 1754, p. 155: "(…) I forewarn the reader that it is very important to put himself exactly in the place of the statue we are going to observe".

two principle theses: (1) the perception of objects is the product of a veritable learning process, and (2) each sense allows the deployment of all of the faculties, but all of the senses do not participate in the same way to the genesis of perception: it is only touch that gives us access to exteriority.

This is to show—notably at odds with his predecessor, that sight by itself does not provide vision of any object and needs to be nurtured—that Condillac takes up the comparison of the blind man's stick and describes what Descartes inevitably passed over without mentioning: the genesis of its manipulation, or, more specifically, of its becoming-organ.

3.2 Mobility Technologies Through the Prism of Condillac

- *The Condillacian theory of the cane*

If he attributes to the figure of the blind man with the cane all of the relevance that Descartes bestowed upon it,[24] and maintains as he did that it can inform vision, Condillac interprets this relevance in an anti-Cartesian sense: according to him, the necessity of learning how to manipulate the cane reveals, through analogy, the historical character of all perception—since we presuppose nothing about its mode of production, nor begin by maintaining that divine laws rule over it. As in the first part of this study, we will now consider the figure of the blind man with the stick for itself, independently of the considerations on vision that it can support.

Removed from Descartes and his semiotic model, Condillac presents a "poetic" theory of perception. According to him, the perceptual effects occasioned by the cane do not rest on any code of mysterious operation, but arise from an elaboration, in first person, of the perceived objet—or from an exteriorization of facts of consciousness, analogous to the process of production, or even of creation[25]: by means of conscious sensed data, the blind man, or rather the statue deprived of vision, constructs for itself the perceived object. The chapter in question can thus be read as a critical re-writing of the pages of the *Optics* that we have been discussing, especially when we note that Condillac follows the exact order of visible qualities that Descartes adopted, and describes in succession the manner in which the statue learns to perceive distance and position, then the magnitude of what will become for it a given object. Yet it is first necessary to determine what a blind person perceives (assumed to be an experiential virgin) when discovering their cane: "The first time that the statue grasps a stick, it knows only the part that it is holding: and it attributes to that part all the sensations that the stick causes" (p. 253). It suffices for

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[24] Condillac [12, p. 253].

[25] Ibid., p. 279: "It is the hand that, guiding vision successively over the different parts of a shape, etches all these parts in memory; it is the hand that, so to say, *guides the engraving tool* when the eyes begin to attribute to the exterior the light and colours that they have first experienced as in themselves". Our emphasis.

our own persuasion to be transported by thought into the mind of this statue, and to speculate on the way in which perception takes place. On this point, Descartes would likely have agreed with Condillac: under the laws unifying the soul and the body, the movements produced by the stick signify, in the soul, the perceptions experienced in the hand. But the abbé continues: "The statue (…) does not know that the stick has extension; and as a result it cannot judge the distances of bodies that it touches with it" (ibid.). If the philosopher deprives the statue of all knowledge of the stick, is because it is necessary to think of it as such to uncover, by sedimented experience, the conditions of its perceptions: can we appreciate, with a cane, the distance of objects, without knowing the length of said cane? A question that would be incidental, if the very essence of perception were not in play: is it the knowledge of the cane that occasions the perceived object, or vice versa? Do I elaborate on my perception, or is it that the object that imprints itself, via my senses, on my mind? For Condillac, the answer seems clear: any mediated perception of an object assumes knowledge of said medium. The anti-Cartesian armament is at the ready.

In the *Optics*, Descartes indeed wrote: "Our blind man holding the two sticks AE and CE (whose length I assume he does not know) (…) can tell (…) where the point E is" (p. 170, our emphasis).

Figure in the *Optics,* p. 136

According to Descartes, it is the very opposite which happens: a blind man has access to the perception of distances without (the necessity of) knowing the length of his stick, because the reconfigured divine laws, mobilizing the "geometrizable" data in his body, suffice to make him perceive. It is such a conception of perception —based on the passivity of the subject—that is the focus of Condillac's contention. Logically, his statue cannot know the position of objects either (p. 253). Condillac specifies the conditions of these perceptions:

> To judge distances by means of a stick, the statue much have touched it throughout its length, and to judge position by the impression that it received from the stick, the statue must, while holding the stick in one hand, study the direction of it with the other. (ibid.)

In the blind spot of the Cartesian theory, Condillac reveals perceptual learning by the subject itself. The incorporation, or the becoming-organ of the cane, requires its active exploration by touch.[26] At the same time, a new mode of perception that Descartes first managed to describe arises:

> The statue no longer attributes the sensations caused by the stick at the end that is in its hand, it feels at the contrary that the hardness or softness of objects on which it places the stick are associated with the opposite end; and *this habit will lead it to distinguish sensations that it did not distinguish previously*. (p. 254, our emphasis)

However, Condillac conceived the novelty of this perceptual mode somewhat differently to Descartes: he does not evoke the occurrence of a sixth sense, but considers that these new perceptions still fall within the sense of touch. According to him, in fact, all of the senses know a genesis whose principle consists of an externalization of sensations: smelling, tasting, hearing, seeing are at first internal (in the statue or in the child), without any perception of the object. It is only under the auspices of touch that the olfactory, gustatory, auditory and visual senses externalize, and are thus distinguished, not only from each other, but between each other: for example, to touch matter allows a distinction between colours, that, initially, were fused together for (and in) consciousness.[27] Touch, for its part, does not know, in ordinary perception, the same process of externalization: as soon as it moves, the statue discovers its body, in material and sensorial extension, which it does not consider as a set of subjective impressions, nor as an object exterior to its being. In the experience of its body, the statue does not externalize the sensations first experienced subjectively, but more so perceives an extension that it knows as "I".[28] On the contrary, the manipulation of the cane produces a projection of tactile sensations equivalent to those of other senses—because the stick constitutes a medium analogous to luminous rays for vision, sound waves for hearing, etc. which does not respond when we touch it, nor do the objects it strikes. Like the externalization of the other senses, that which is occasioned by the cane produces a distinction between sensations experienced at first in the same organ, in this case the hand—sensations, which, for Condillac, were sensed, but not known. This is why, according to him, the stick gives rise to perceptions, which, all the while having a tactile nature, are well and truly original. By externalizing itself in perception, consciousness manages on its own, and distinguishes its sensations (which thus delineate objects), feelings and passions (which remain internal).

Thus, everything happens as if semiotism paradoxically prevented thinking of perceptual learning[29]: while the Cartesian theory of bypassing divine laws makes it difficult, almost impossible to conceive of the genesis of perception in the blind man with the cane, Condillac's "poetic" conception, which takes its origin in the

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[26] Here we are far from the alleged passivity of the body, but also of the mind, to which classic empiricism would be condemned.

[27] This principle also works for sounds, and the other sensible qualities.

[28] Condillac [12, p. 234].

[29] On the relationships between semiotic conceptions and geometric conceptions of perception, see [8].

statue's sensations themselves, and shows how the perceived object is always constructed with the hands, makes it conceivable, and even probable.

Such a conception deviates even more from Descartes' in that it refuses to condition the perception of geometric laws. Indeed, here is what Condillac writes on learning about magnitude: "In order to establish the distance between the ends of two crossed sticks, a geometer need only establish the magnitudes of the angles and the sides" [12, p. 254]. But, according to him, it is not in this way that the statue operates:

> The statue cannot pursue a method with so much precision. But it knows roughly the size of the sticks, how much they are inclined, the point at which they are crossed; and it judges that the ends which touch various objects converge or diverge in the same proportion as the ends that it as in hand. Thus, we readily imagine how as a result of various trials the statue will formulate *a kind of geometry* and will judge the size of objects with the aid of two sticks. (p. 254–255, our emphasis)

Thus, the statue does not apply any trigonometrical rule to what it perceives: now it has learned to project its sensations away from itself, it feels at the same time the gap between its hands[30] and that of its sticks, and, by the movements that they imprint, discover their different relationships. It could thus not only perceive the magnitude of the bodies it encounters, but also express this magnitude in any unit of measurement, relative to its body parts. The perception of magnitude by means of the cane thus does not come from calculation, but from the acquisition of sensorimotor schemas.[31]

Of course, geometry is involved: these schemas are perceptions of relationships. But it is a matter of the geometry inherent to bodily experience, deprived of signs, as formalized calculations:

> Thus, knowledge of the principles of geometry would be totally useless for our statue (…). It would be thus quite superfluous to conjecture that the statue has innate ideas about size and position: it needs only hands. (p. 255)

This last proposition is not in contradiction with the Cartesian theory: for Descartes, the device of divine institution precisely enables the explanation of perception without placing an innate geometry in the spirit of the subject. The divide between the two theories must not, however, be underestimated. If the Cartesian blind man only perceived "*as if* by a natural geometry" [18, 19, p. 170, our emphasis], because he does not calculate any more than his Condillacian cousin, his perceptions are the effect of laws that geometrize in his body. Instead, Condillac's blind statue is not the plaything of any theorem. The fact that it must learn to perceive and make its own geometry "blindly groping along" does not attest to the actualization of a disruption of the divine laws, but the powerlessness of the laws of optics to generate perception. The blind man with the cane is himself the author of what he perceives.

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[30] From here it is a matter of proprioceptive sensations.

[31] On this notion of sensorimotor schemas, see Lenay et al., op. cit.

– *ICT through the prism of Condillac*

Following Descartes, Condillac teaches us that mobility technologies do not restore sight to the blind.[32] For the author of *Treatise on the Sensations*, they give them access to perceptions that have the distinction of taking place away from the body, or moreover, by augmenting the body. By the phenomenon of objectification that results, these perceptions show that touch can operate like the other senses, and project its sensations. Yet, this is exactly what Bach-y-Rita describes: "After sufficient training with the TVSS, our subjects reported experiencing the image in space, instead of in the skin" (op. cit., p. 500). The researcher elsewhere situates his invention in continuation with the blind man's stick:

> Similarly, a blind person using a long cane does not perceive the resulting stimulation as being in the hand, but correctly locates it in the ground being swept with the cane, and a person writing with a pen does not perceive the contact as being on the fingers, but rather locates it subjectively on the page. (ibid.)

In addition, Bach-y-Rita highlights what Condillac shows as a necessity, namely the manual and corporal exploration of the perceptual medium (p. 497). Through the prism of the Condillacian theory of perception, mobility technologies are thus conceivable, but not as devices through which (continued) creation alters the union of the soul and the body, but as instruments analogous to the organs of sense, through which the human creation of the perceived world takes place. The break with Descartes is complete. What the author of the *Optics* could only give the principle of, namely the *use* of ICT, Condillac produces in thought, through a radically revamped method.

But if Bach-y-Rita's observations already express all the above, to what end could we employ a Condillacian theory? To assert that, from the eighteenth century, a philosopher had established that the body in movement was full of new perceptions? The interest is not only historical. As we judge it, Condillac's thought enables the avoidance of two errors. Firstly, where Bach-y-Rita writes that the subjects endowed with TVSS must know of the mechanism, it could not be considered that a knowledge of the internal operation of the device is required for its usage: if it is necessary for its incorporation, to explore the medium with which one perceives, it is not to know its machinery—it is not a mechanism that is known, but the sensorimotor schemas that one must acquire. As Charles Lenay and François-David Sebbah (after, by their own acknowledgement, Merleau-Ponty) have expressed:

> (…) we abandon the conception that the subject would receive information then perform calculations on them to identity objects and produce representations in an internal space. To the contrary, it is through their action that the subject seeks and constructs rules of consistent relations between sensation and action (our translation, op. cit., p. 57)

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[32] In the debate that sees contemporary researchers in opposition on this subject, our philosophers would thus agree with Degenaar [15], Warren et al. [35], and find Bach-y-Rita [3] and [31] erroneous.

Secondly, when Bach-y-Rita shows, regarding a TVSS user who is tasked with batting a rolling ball, that he needs, to achieve this, to "calculate the time it would take to reach the edge of the table, calculate the position of the table (…), identify the location in his "visual" field of the bat, and correctly time his movement of the bat in order to bat the ball" (op. cit., p. 501), it could not be the case to believe that such a series of perceptions and actions constitute, strictly speaking, the effect of a calculation. In effect, Condillac taught us to not mistake the applicability of mathematics to perceptual phenomena for the development, in the facts of consciousness, of perception itself: it is not because a phenomenon can be expressed mathematically that it is the effect of a causality, and even more so of a mathematical knowledge. A geometer would not any better catch said rolling ball than any other individual. Yet, it is not any more a matter of eliminating the geometry of perception: during the exercise with the ball, as in the assessment of magnitude, the perception of relationships gradually emerges from the movement of the body itself. For Condillac, these are perceptual relationships, issued from an "empirical geometry" which, through abstraction, becomes geometric theorems. Far from being the cause of perceptions, mathematics constitute its effects.

Thus, because it is drawn from the difficulties of Cartesian philosophy, the Condillacian theory of perception sheds light on mobility technologies more than Descartes would have done: cleared of perceptual semiotism, which certainly had merit to explain their operation, but makes their use difficult to conceive, Condillac's theory, based on the suspension of causal considerations and the objectification of sensations, can account for the genesis of perception and the active role of the perceiving subject. Far from thinking of perception in terms of a mental "tableau", or painting, imprinted in the mind by presupposed objects, Condillac develops, in 1754, a dynamic and poetic conception of perceptual phenomena, and makes a paradigm of the blind man with the stick. However, there will be those who ask what interest there is in mobilizing empiricism, when phenomenology no longer needs to prove its fertility. This is why in last place we will weigh Condillac up against the most pivotal of contemporary philosophers on perception: Maurice Merleau-Ponty, to examine the theoretical and practical benefits of Condillacian empiricism.

4 Condillac Confronted with Merleau-Ponty

Phenomenology in general, and that of Merleau-Ponty in particular, are regularly invoked when it comes to distinguishing the space of science from that, irreducible to it, of perception,[33] and notably when insisting on the dynamic and incarnate character of the perceptual act, which is not conceptualizable in the classic terms of "representation" or of "tableau". For what concerns us here more specifically, phenomenology comes to serve the understanding of ICT and of their use, which, in

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[33] For example, see [13].

turn, comes to confirm his assertions: TVSS or newer devices support the Merleau-Pontian thesis of the ability of technical objects to reconfigure “the actualization, the implementation, of the constituent power residing in one’s own body” (our translation, Lenay et al. op. cit., p. 81). In order to appreciate what these devices have to tell us, what is different, or what they add when we consider them through the prism of the *Treatise on the Sensations*, we will start by examining how, for his part, Merleau-Ponty conceptualizes the cane of the blind man, differentiating it from what he assesses to be a wrong conception—that is to say, Descartes’, but which is in reality closer to Condillac’s. We will, however, see that Merleau-Ponty’s objections do not pull down the sensualist conception of perception, and will eventually show how mobility technologies can be conceived of as Condillacian instruments.

4.1 The Merleau-Pontian Theory of the Cane

In Chap. 4 of the first part of his *Phenomenology of Perception*, Merleau-Ponty undertakes the task of illuminating the concept of the “synthesis of one’s own body” through the analysis of habit, and makes the following observation:

> Learning to find one’s way among things with a stick, which we gave a little earlier as an example of motor habit, is equally an example of perceptual habit. Once the stick has become a familiar instrument, the world of feelable things recedes and now begins, not at the outer skin of the hand, but at the end of the stick. (p. 152)

For Merleau-Ponty, as for Condillac before him, the stick of the blind man does not allow him to see, but to extend the perceptions of touch beyond his earthly body, and thus of the body itself beyond its natural organs. And, like Condillac, but also Descartes, Merleau-Ponty considers that the perceptions mediated by the stick are not of the same kind as those that the hand enables, and instead come from an new universe: perceptual habit is, for him, in general, synonymous with “possession of a world” (p. 153)—it is precisely this that the stick reveals. But before formulating this thesis, Merleau-Ponty is careful to indicate, in order to challenge, the interpretation that we are tempted to make on the emergence of this new world:

> One is tempted to say that through the sensations produced by the pressure of the stick on the hand, the blind man builds up the stick along with its various positions, and that the latter then mediate a second order object, the external thing. (p. 152)

However, this double construction, that of the stick, then the object it reaches, strictly corresponds to the Condillacian theory of the cane—according to which, we will remember, the perception of the object is conditioned by that of the stick, and thus takes place in two stages. But, as Merleau-Ponty has previously indicated:

> In the exploration of things, the length of the stick does not enter expressly as a middle term: the blind man is rather aware of it through the position of objects than of the position of objects through it. (p. 143)

The length of the stick inevitably intervenes in the apprehension of objects (indissociable from the stick itself, the length conditions the *possibility* of perception) but does not act "expressly", or subjectively, as mediate perception. The perception of the stick is rather, according to Merleau-Ponty, the *effect* of its manipulation and of objective encounters—of the kind that—where his view diverges from Condillac's—perceptual habit (which is, at the same time, always motor) modifies the originary spatiality of the body itself. It is for this reason that, for Merleau-Ponty, technical objects reconfigure the constituent power of the body itself: in mediated perception, emerges, by habit, a new constituent power, giving new objects, which at the same time form its realization. According to Merleau-Ponty, the blind man's cane thus constitutes the object of a becoming-organ, which is not the instrument of bypassing divine laws (Descartes), or, as we will see, that of the objectification of sensations (Condillac), but the site of a reciprocal constitution of an augmented body and its new objects. The cane reveals, by the same token, the reciprocal constitution of the subject and the object, at work, in the same way, in ordinary perception.

Continuing his description of the interpretation (tempting but faulty) of the genesis of perception, Merleau-Ponty then writes "It would appear in this case that perception is always a reading off from the same sensory data, but constantly accelerated (…)" (p. 152). Yet, when Condillac describes how his statue gradually learns to perceive a single object, instead of the two objects that his crossed sticks make its firstly (and falsely) apprehend, it is exactly this acquisition of speed through the repetition of experience that he describes. Deprived of habit, the statue "will often believe that it has touched two objects when in fact it has only touched one" (*Treatise on the Sensations*, p. 253–254)[34] . For Condillac, the correction of this belief rests on the acquisition of a judgement, hidden from consciousness by habit, that shortens its duration, and in some way, speeds up the time taken:

> This judgement will be at first only the result of quite slow reasoning. The statue will say to itself as it were: these sticks can only cross if the extremity of the one in my left hand is on my right. As a result, the objects that they touch are in the opposite positions from those of my hands (…). Subsequently, this line of reasoning will become so familiar and will be executed so rapidly that the statue will judge the positions of objects without appearing to give the least attention to the positions of its hands. (p. 254)

The "without appearing to" is decisive: as the premise of the reasoning that the statue continues to progress in this position, the perception of the sticks by his hands would not be eliminated in favour of the objects perceived at the other end, nor become unconscious—since his *Essay on the origin of human knowledge*, Condillac rejects the Leibnizian thesis of "small perceptions" in the name of his own method, based on the primacy of perception on consciousness in the development of knowledge. Thus, the conception that Merleau-Ponty challenges in these

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[34] On his side, Descartes only indicated, on the topic of his blind tailor and manual exploration, that he "does not judge a body to be double although he touches it with his two hands" (18, 19, p. 170)—without describing the process which according to him arises out of bypassing the laws of the union.

pages of the *Phenomenology* is much closer to Condillac's than to Descartes', which, as we have seen, rests within the laws of the union—and not in the consciousness of the subject—the principle of perceptual efficacy.

For Merleau-Ponty, the construction of a perceptual world by means of a stick does not come out "of any quick estimate or any comparison between the objective length of the stick and the objective distance away of the goal to be reached" (p. 143)[35]. Such an explanation of mediated perception (and, hence, ordinary perception) amounts to, according to him, giving oneself that which we claim to realize, that is, the world: that objects are perceived from some initial data presupposes the position, that is to say, in the end, the perception of these objects. This circle of the causal (or causalist) explanation of perception, that he implicitly mobilizes here, constitutes the principle objection that Merleau-Ponty addresses to the scientific (more precisely, physicist) point of view, to which he contrasts understanding, and the immediate apprehension of meaning at work in the perceptual act.[36]

However, if it so seems, at first, that he has the Condillacian (or at the least the empiricist[37]) theory of the blind man's cane in his sights, Merleau-Ponty moreso targets, in these pages, intellectualism, and more specifically, perceptual Cartesianism. Here indeed is what he writes, quickly indicating the interpretation that he judges faulty: "But habit does not *consist* in interpreting the pressures of the stick on the hand as indications of certain positions of the stick, and these as signs of an external objects, since it *relieves us of the necessity* of doing so" (p. 152). According to him, the experienced blind man does not perceive two objects, the stick and that which it touches, but, thanks to the repetition of experience, the latter to the exclusion of the first. The individual who, inversely, needs to perceive their arm in order to apprehend an object, suffers from a perceptual disturbance (for example, psychic blindness), whose nature consists precisely of producing a sequencing, and requiring an analysis of the perceptual act, of which the healthy individual has no need. In so-called "normal" perception, under which touch mediated by a stick can be categorized, there are never two stages that succeed one another: if the blind man starts by perceiving simultaneously his cane and the object it strikes, according to a reciprocal constitution of one by the other, the habit has the effect of erasing the perception of the cane in favour of that which it touches, and which, in turn, modifies the boundaries of myself and not-myself: the object recedes, while the subject, or lived body, augments to the becoming-organ of the stick. However, it is important for us here to note that through the eyes of Merleau-Ponty "the pressures of the stick on the hand", which, according to the faulty interpretation, persist in final perception, constituting "signs" that it is a

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[35] We specify here that this is not exactly what Condillac maintained. The reasoning that his statue performs does not carry over pre-existing objective data—we will see that he does not fall into the circle that Merleau–Ponty implicitly denounces here.

[36] On the idea that such a "meaning" can be interpreted in rationalist terms, and thus take part in the contemporary quarrel over conceptual contents of perception, see Bimbenet [6], in particular p. 22.

[37] It would seem that Merleau–Ponty has never read Condillac.

matter of “interpreting”. Yet, according to him, all semiotism is an intellectualism, and reciprocally:

> Intellectualism cannot conceive any passage from the perspective to the thing itself, or from sign to significance otherwise than as an interpretation, an apperception, a cognitive intention. (p. 152)

And we are aware that as such it must be rejected. Moreover, according to Merleau-Ponty, empiricism features nothing of a theory that makes a construction (whether sensory or intellectual) of the perceived world: the “empiricist consciousness”, according to him, “constitutes nothing at all” (p. 28), but merely passively receives “impressions” or “sensations”, which, combined together, form objects. Under this framework, perception is conceived of as “purely a matter of knowledge, a progressive noting down of qualities and of their most habitual distribution, and the perceiving subject approaches the world as the scientist approaches his experiments” (p. 24). This Merleau-Pontian reading, now widespread, is perhaps issued from the generalization, on empiricism in general, of the principle traits of Humean philosophy, via the works of Kant, who, for posterity, made of Hume the principal representative of the empiricist philosophy. Insofar as Condillac is manifestly situated diametrically opposite to this reading, should we say that Merleau-Ponty’s texts reveal, conversely, the intellectualism of the *Treatise on the Sensations*?

Certainly, Condillac conditions certain mediated perceptions as the actualization of a “reasoning”. Moreover, if this conditioning seems restricted to perceptions mediated by *two* sticks, and does not apply to the manipulation of the ordinary cane, the author of *Treatise on the Sensations* writes elsewhere that “*judgments are mixed in with our sensations* whatever the sensory organ by which they are transmitted to the mind” (p. 289, our emphasis). For example, to acquire by sight the idea of the triangle, it is necessary to bring a whole series of judgements:

> It [*sc.* the eye] grasps the whole of the simplest shape only when it has analyzed it, that is, when it has observed all its parts in succession. It must make a judgement about each particular part, and another judgement that combines them. It must say to itself: here is one side, here is a second, and here is a third; here is a space bounded by these three sides, and from all that, this triangle results. (p. 217)

Likewise, the blind man that manipulates his stick objectifies his first sensations and transforms them into perceptions (of objects) by performing a series of judgements. This conception is the one and the same that Merleau-Ponty classifies as “intellectualist” and which tasks himself with challenging.

[38] According to him, the principle thesis that we need to dismiss is precisely that which makes judgement the operator of the transformation of sensation into perception. If, undeniably, Condillac makes it his, and consequently considers that the objectification of sensations, or the act that we have classified as “poetic”, is performed under the auspices of judgement, as he sees it, intellectualism is more of as

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[38] On the Merleau-Pontian critique of intellectualism, see L. Angelino [2]

aside to the reduction of perception into sense impressions: according to him, to affirm that to perceive consists in receiving, via the five senses, objects already formed, accounts to an explanation of perception by a device susceptible to producing shapes in the mind, i.e. by laws, mathematical but hidden from consciousness, of the union of the soul and the body—that is, at the end, and, as Merleau-Ponty will say, under the presupposition that there is something to explain. Since he conditions the perceptions mediated by the stick as the actualization of a reasoning (or a series of judgements), Condillac avoids this circle: it is not a matter of, for his statue, comparing the series of objective data, provided in advance, but, through attention, to *generate* what Descartes presupposed, that is, sensed objects.

Reciprocally, the position of a series of judgements at the heart of perception is not, for Condillac, anything but that intellectualist. Let us now turn back to the concept of "empirical geometry", remembering that it operates without signs or symbols, by the acquisition of sensorimotor schemas: it has come time to build from it the conditions of possibilities. In other words, how can one geometrize without reasoning, or even have consciousness of judging? For the author of *Treatise on the Sensations*—and therein lies his principal *tour de force*—an empirical geometry can inform our perceptions, because the judgements, like reflection, desires, and passions, are reducible to "transformed sensations".[39] In effect, for Condillac, once we receive two sensations simultaneously, we sense that one is not the other: we compare them. Yet to compare is none other than to judge: "A judgement is (…) only the perception of a relation between two ideas that are compared" (p. 180). In other words, a judgement is none other than an establishing of relations between sensations.

Far from making an exception to such sensualism, the blind man with the stick makes a contribution to its exposition, and attests that the manipulation of the cane elicits the acquisition of new perceptions of relationships, which are purely sensory: the individual that learns to perceive with a stick is not conscious of reasoning, because his judgements are solely the sequence of sensations. Restored back to sensation, the act of judging passes necessarily unnoticed by a consciousness that seeks within itself an intellectual act, conceived as a way of understanding. Thus envisaged, perception has nothing of a "mind's inspection", understood as a synthesis of the soul actualized on the affected body. To the extent that judgements come from what is sensed, perception seems moreso the site of the reciprocal formation, via the body in movement, of the perceiving subject and the object perceived. Thus, far from revealing the intellectualist dimension of Condillac's thought, the Merleau-Pontian analyses highlight its originality and the impossibility to reduce the classic theories to what the *Phenomenology of Perception* says. However, if he seems to disregard the Condillacian sensualism, Merleau-Ponty has nonetheless grasped, in empiricism, a dimension closely corresponding to the theses

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[39] Cf. 'The Plan of This Work', p. 171: "Judgement, reflection, desires, passions and so forth are only sensation itself differently transformed".

of Condillac, and whose examination will also contribute to appreciating their theoretical and practical fertility.

4.2 Theoretical and Practical Contributions of the Condillacian Theory of Perception

If Merleau-Ponty is mistaken when he classifies as “intellectualist” any conception that places judgements at the heart of perception, and also when he reduces empiricism to a theory of perceptual passivity, he does, however, have a good grasp on the primacy that it accords to the concept of sensation. A touch coarser than intellectualism, in his opinion empiricism holds several of its own fictions, with sensation figuring first and foremost—of which the first chapters of the *Phenomenology* intend to show nothing less than its inexistence.

By no means constituent, but instead constituted by the (empiricist, but also Kantian) subject who, a posteriori, separates matter and form of the sensory, sensation is, as such, a pure fiction. In other words, all consciousness, according to Merleau-Ponty, is necessarily consciousness of objects. It suffices to think of perception to notice this: never do we have sensation of hot, of cold, of yellow or of red, that appear to us other than under the features of one or multiple objects, even if they be poorly determined. Thus, for Merleau-Ponty, perception is not derived from sensation, and does not consist of an objectification of the subjective. In contrast to Condillac, who maintains that all consciousness is, before all else, a consciousness of the self, and only becomes consciousness of an object through touch and movements of the body, Merleau-Ponty writes:

> More generally, it is the very notion of the immediate which is transformed: henceforth the immediate is no longer the impression, the object which is one with the subject, but the meaning, the structure, the spontaneous arrangement of parts. (p. 58)

If there is a perceptual learning period in *Phenomenology of Perception*, it consists of a circulation of less determined objects and more determined objects, and nowhere a transition from (subjective) sensation to (objective) perception. Certainly, as [9] has highlighted, the phenomenological critique of sensation as a fiction does not quite reach Condillacian sensualism, insofar as Condillac himself, from the *Essay* onwards, maintains that as adults, we no longer have sensations—but only perceptions, or ideas of objects. However, Merleau-Ponty generalises somewhat this empiricist thesis and affirms that we have never done anything other but perceive—what Condillac sets himself precisely to challenging. The Merleau-Pontian refusal to keep sensation as origin derives equally from his rejection of any genetic conception of the mind: according to him “all idea of a genesis of mind is a hybrid idea, because it puts back into time the mind for which time exists” (p. 45, note). We have here, it seems, a new obstacle of Kantian origin for the appreciation of continental empiricism.

If, for Merleau-Ponty as for the abbé, the cane allows the tactile word to retreat, and enables, far from all semiotism, a "projective" conception of ordinary perception[40] , his conception thus has nothing "poetic" about it, in the sense that we encountered previously. The Merleau-Pontian blind man with the stick does not spread out into the world, does not construct objects through the means of his interiority, but encounters otherness and circulates in a world of sensory objects, to which his body itself belongs. Yet, there is a first advantage, on the theoretical level, to do the inverse and base the genesis of perception on the level of sensation: unlike Merleau-Ponty, Condillac theorizes the apparition of objects for consciousness and is not satisfied with the phenomenological "there is" ("*il y a*"). If, through *epoché* the former intends to find the emergence of the object, the latter goes further back, by virtue of the fictive nature of the statue, to a state prior to objective perception, and therein conceives of its formation. In addition to the theoretical gains for empiricism on this point, we can also highlight the practical benefits. Not only, as we have seen, does the Condillacian conception of the blind man's cane provide, based on the objectification of sensation, a frame of thought for the examination of mobility technologies, but presents the advantage, over phenomenology, of joining up with Bach-y-Rita's descriptions, which, support it back in turn[41]: everything that Merleau-Ponty rejects as faulty interpretation of the blind man's cane—the constitution of the object perceived by that of the medium used, the presence of judgements in the genesis of perception, the transition from sensation to perception, and that we find, on the other hand, word for word in *Treatise on the Sensations*, is also found verbatim from the pen of Bach-y-Rita. We will not quote here the passages in their entirety, but only these lines, in which Bach-y-Rita implicitly distinguishes sensation and perception, and insists on the ability of the subject to move from one to the other:

> Subjects using the TVSS learn to treat the information arriving at the skin in its proper context. Thus, at one moment the information arriving at the skin has been gathered by the TV camera, but at another it relates to the usual cutaneous information (pressure, tickle, wetness, etc.). The subject is not confused; when he/she scratches his/her back under the matrix nothing is "seen." Even during task performance with the sensory system, the subject can perceive purely tactile sensations when asked to concentrate on these sensations. (op. cit., p. 501)

The sensations felt on the back do not constitute the simple "objective" conditions necessary for distance perception—as does the length of the stick for Merleau-Ponty, who refuses however, that its *knowledge* intervenes in the genesis of perception. Not only do these sensations constitute the subjective conditions of the perceptions of objects, but as evidenced by the fact that it is possible at any time to return to them, they do not end up eliminating themselves to their own benefit.

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[40] "In the gaze we have at our disposal a natural instrument analogous to the blind man's stick" [29, p. 153]. "I have only to see something to know how to reach it and deal with it" [30, p. 124].

[41] On the relationships between ICT and philosophical theories, see, for example, Declerck, op. cit., p. 207.

As a result, attention is not, as Merleau-Ponty believes, reducible to a creative faculty[42]: in accordance with what Condillac says, it is moreso what is given that creates it, or at the very least elicits it in experience—tickling, for example.

We will highlight a final theoretical benefit of Condillacian empiricism: its ability to conceptualize, under the term “transformed sensations”, what intellectualism failed to consider—namely, the “mystery” of a perception steeped in judgements, which, however, elude consciousness. We have already come across this: once we show that to judge is to sense, the problem is resolved. Ignorant of this solution, Merleau-Ponty attributes to the body the act of synthesis of which, according to him, intellectualism made of the soul the only subject: “The cultivation of habit is indeed the grasping of a significance, but it is the motor grasping of a motor significance” (p. 143). After having taken the example of dance and highlighted, rightly, that its learning does not consist of an analysis of the formula of movement and its application to the body-object, he adds: “As has often been said, it is the body which ‘catches’ and ‘comprehends’ movement” (ibid.). Similarly, he continues a few lines further on:

> If I want to get used to a stick, I try it by touching a few things with it, and eventually I have it ‘well in hand’, I can see what things are ‘within reach’ or out of reach of my stick. (ibid.)

Merleau-Ponty can thus conclude that “habit has its abode neither in thought nor in the objective body, but in the body as mediator of a world” (p. 145). But how are we to conceive of this “knowledge in the hands” (p. 144)? If, for Condillac no more than for Merleau-Ponty, objects perceived by virtue of the cane are not “as objective positions in relation to the objective position occupied by our body; they mark, in our vicinity, the varying range of our aims and our gestures” (p. 143), the *Treatise on the Sensations* does not situate the principle of habit or of the genesis of perception in the body to the exclusion of thought: his concept of “transformed sensation”—in this case, sensory judgement—precisely overcomes the alternative, and in effect the dualism, to which Merleau-Ponty remains partly prisoner[43]: once we understand that the mind is but itself a collection of transformed sensations, we can recognize in it a capability for synthesis, without placing it in a position of control from above in regard to its body and to objects, but above all, we will be able to say what it is that constitutes this “knowledge in the hands” (of perceptions of relationships), and guide the learning of mobility technologies from there. Instead, the Merleau-Pontian discourse condemns itself, on this point, to resort to quotation marks, to mobilize expressions of opinion—largely remaining within intellection—and, conversely, going beyond the intelligible to take on the aspect of a poetics of perception, in the narrow sense of the term.

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[42] P. 28: “(…) the two doctrines, then, have this idea in common that attention creates nothing, since a world of impressions in itself or a universe of determining thought are equally independent of the action of mind”.

[43] On the persistence of a certain dualism in Merleau–Ponty, see Barbaras [5, pp. 94–95].

5 Conclusion

Among the classic theories of perception, we have selected two, for the prime position they occupy to with regards to each other on the topic on the blind man's cane. We have firstly examined the manner in which Cartesian philosophy conceived of this instrument of mobility *and* of perception, and we have shown that, beyond the comparison that he establishes in the *Optics*, between the way in which a blind man perceives by means of a stick, and the process of engendering vision, Descartes informs our knowledge of the cane for itself. On the contrary to what a quick reading of Cartesianism may suggest, the author of the *Optics* does not reduce it to a mechanical appendage of a bodily machine, on which the soul would learn to measure, calculate and finally construct objects which can be reduced to portions of space or extension. He much more envisages the cane as analogous to a new organ, in that it bestows upon the blind man a sixth sense and opens up to him a new universe, composed of perceptions, in light of our own natural sensibility, are neither entirely visual, nor entirely tactile, but well and truly "sensible". These perceptions do not arise from a subject's calculations on first sensations, but result from a reconfiguration, through habit, of the laws uniting the soul and the body, which, for their own part, continue to follow geometrical theorems. The Cartesian conception of natural perception allows us, all things considered, to bypass the latter through the institution of a new code, and at the same time, make sense of any device that, like TVSS, creates perceptions. In the terms of contemporary neuroscience, we would say that neuroplasticity is such that it enables ordinary corporal impulses to signify extra-ordinary perceptions.

If Descartes could deploy this conception of the cane only by means of a thought experiment, if he had at hand a good "point of view" for thinking of the way in which a blind person learns to step into this new universe; his use of the blind man's stick, as much as it remains subordinate to a causalist *and* semiotic theory of vision, had nevertheless restricted him to not being able to offer an account of this process of learning: under this framework, we do not understand how the perceiving subject can associate new meanings to cerebral movements of which he has neither knowledge, nor even consciousness—which is, however, required from the moment we make recourse to the concept of "institution". Perceptual semiotism, at least conceived of as such, seems destined to fail.

This is why we have considered a second theory, that of Condillac's *Treatise on the Sensations*, based on a rejection of the causalist approach and the idea of the union of the soul and the body governed by a set of pre-instituted laws. For the abbé, the blind man's cane is the model of a poetic conception of perception, in which perceived objects constitute the projections of sensations, constructed by the subject himself through the movements of his body, driven by the pursuit of pleasure. In this framework, the cane is not an instrument of a mysterious reconfiguration of the laws of the union, but an objectification of sensations analogous to those that are produced for the four other senses during the first few months of our life. This objectification is realized through judgements, realized by the subject himself, which are not pre-existent to sensations, but emerge from them, and are nothing but the sensory apprehension of their relationships. The cane appears thus as the means, pre-constituted by the movements of the body by which the perceived object and the subject constitute one another. By itself, the Condillacian exploration of the cane thus suffices to rectify the conception that we commonly make about empiricism.

We have lastly moved closer the Condillacian theory of the stick with that which Merleau-Ponty rejects in the *Phenomenology of Perception*, and introduced his defence, in which the blind man's cane constitutes one of the organ-objects which, along with the car, the hat, and the typewriter, allow us to think afresh about the body and its objects: far from being an object of thought for a disembodied mind, the body constitutes, in his view, a "lived body", which finds itself with the perceived object in a reciprocal relationship. An instrument that is susceptible to, by habit, augmenting the body itself, the cane, in the same exact manner, constitutes its objects at the same time that it is constituted by them. Having become analogous to an organ, it at once seizes its objects, without the spirit reflecting on any of its (alleged) sensations. For Merleau-Ponty, perceptual development does not consist of a transition from sensation to perception, but an encounter better determined in relation to otherness. In the end, we have emphasized that, on this point, ICT—at least the TVSS of Bach-y-Rita—corresponds more to Condillacian descriptions, which, in turn, illuminates them better than the phenomenology of Merleau-Ponty. First and foremost, Condillac's philosophy merits putting the concept of "sensation" in prime position, which mobility technologies do not seem able to do without. It thus reveals that mediated perception enables not only the emergence of new worlds, but also new judgements, and participates in the genesis of the mind[44]. It should now be a matter of appreciating the fruitfulness of sensualism in the light of newer technologies, and to examine how they can in turn actualize and nourish it.

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[44] On the reversal of the form/consciousness relationship in later Merleau-Ponty, see Barbaras 4, p. 162.

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Part II

Neuro-cognitive Basis of Space Perception for Mobility

The Multisensory Blind Brain

Vanessa Harrar, Sébrina Aubin, Daniel-Robert Chebat, Ron Kupers and Maurice Ptito

1 Introduction

The brain is a fascinating organ. It has the incredible ability to turn electrical, mechanical, and chemical energy into multisensory knowledge about the world. Neuroscientists are taught that the brain is divided into regions—each responsible for interpreting information from a single sense, except a few integrative multisensory areas whose role is to combine information from the different senses (Fig. 1). For example, the posterior part of the brain, the occipital cortex, interprets visual information; the area above the ears, the temporal cortex, interprets auditory information; above from that towards the middle of the head is the somatosensory sulcus, which interprets tactile stimulation and generates motor actions. This idea that the mind is composed of distinct faculties, with separate seats in the brain, took origin from same kind of categorical location-based ideology as sixteenth century

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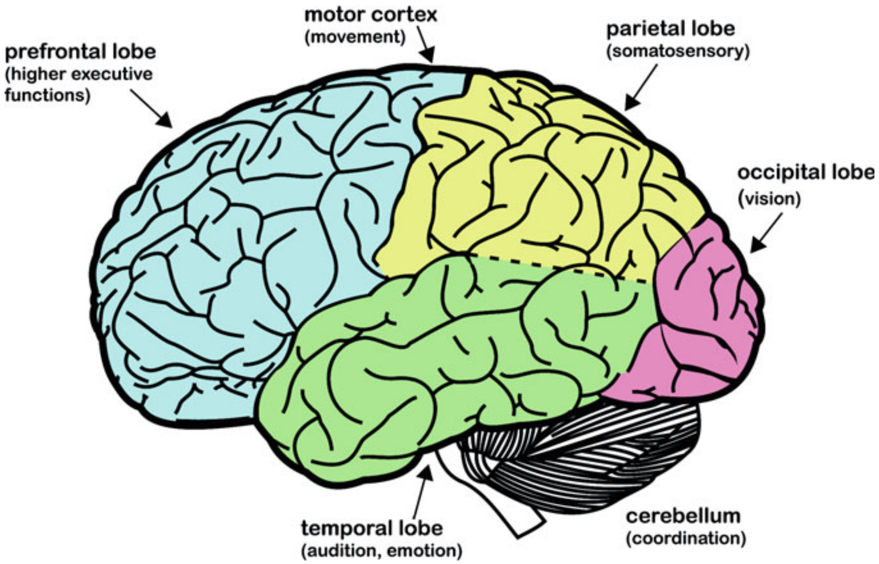

Fig. 1 Lateral view of the human brain indicating the various lobes and their primary functions. Modified from *Anatomy of the Human Body*, Gray H, Fig. 728 (1918)

phrenology. Yet, we now know that this specificity hypothesis is largely incomplete and a fallacy. Studies into the plasticity in the blind brain have revealed that the occipital cortex is not solely reserved for visual functions. In fact, blind people trained in spatial tasks, such as braille reading, or on sensory substitution devices, need the occipital cortex to interpret these non-visual stimulations.

In the second and third sections of this chapter, we will review the literature on the traditional multisensory brain areas. We argue that multisensory integration is a core aspect of human survival. In the fourth and fifth sections, we will review the literature on multisensory integration in areas of the brain that were classically considered to be modality-specific, and demonstrate that these areas are also active in the integration of information from multiple modal sources. We will debunk the myth that the visual areas of the brain are strictly visual. In the final section of this chapter, we argue in favour of the idea that the brain is divided according to function rather than modality. Information is, therefore, represented in an amodal manner, i.e. in a way that it is abstracted from its modal source. We further argue that cognitive processes of memory and even mental imagery can be amodal in nature.

The impressive multisensory plasticity of the blind brain can, therefore, be capitalised on in order to improve high-tech rehabilitation devices for people with decreased visual abilities. Further, this evidence for cross-modal and cross-cortical plasticity suggest possibilities of rehabilitating patients with brain trauma (e.g. stroke) by accessing the latent multisensory pathways within the brain.

2 What Is Multisensory?

There are a few areas of the brain that have been labelled as multisensory areas, and appear to be particularly important for integrating the information from multiple senses. Multisensory areas are composed of multisensory neurons—meaning neurons that respond to stimuli from multiple modalities. For example, neurons in the deep layers of the cat's superior colliculus (SC) respond to visual, auditory, and somatosensory stimuli [92, 134], and with overlapping receptive fields [131]. Thus, a stimulus located on the bottom left of the cat's sensory field could activate the same neuron in the SC whether the stimulus is visual, auditory, or a brush of the whisker. What makes these neurons particularly interesting is that they fire more frequently when stimulation come from two modalities, as compared to only one modality [132, 135]. These superadditive responses exceed the strongest unisensory response, and often exceed even the sum of the unisensory responses.

Investigations into superadditive neurons have revealed the principles of multisensory integration. The conditions that lead to increased neuronal activity also lead to behavioural improvements; an enhanced signal would, thus, improve detection (and lower threshold), allowing for faster responses with less variability—especially for eye movements [30, 31, 37, 133]. The conditions under which superadditivity and thus multisensory integration are likely to occur include: spatial and temporal proximity [44], and inverse effectiveness [93]. That is, for stimuli to be combined into a single event, they must occur in the same location (spatial proximity), at the same time (temporal proximity), and should be relatively weak (inverse effectiveness) in order to enable a substantial superadditive enhancement effect. Of course, without boundaries (space and time) all stimuli would collapse together. The question then becomes, how do multisensory neurons learn which stimuli go together?

Multisensory integration is thought to have developed to maximise our chance of survival by minimising the unisensory limitations of each sensory system. For example, the eye transduces light at a rather slow rate and has a coarse perception of time. In contrast, the auditory system has a mechanical transduction, which is relatively fast and temporally precise, but is limited in the spatial plane. Thus, our ability to spatially locate sounds is much less precise than our ability to locate visual stimuli. When we are faced with danger, the survival predicament dictates that we need to immediately detect the origin of the growling animal and either run away or prepare to fight. Many studies have demonstrated that the multisensory integration within the SC allows us to orient our eyes to a sound. The theory is that the sound is used to detect a rough location of the threat, and vision is used to determine what is threatening. In less dangerous conditions, tested in laboratory settings, it has been established that multisensory integration can sometimes be "optimal"—our perception is a weighted sum of the total information available, with more weight afforded to the sense with the least variability [1, 39]. Multisensory integration, thus, optimises all four f's necessary for our survival: *fight*, *flight*, *feeding,* and *fertility*.

Eating is an important multisensory activity [7]. Chefs have known this intuitively by making food that not only taste good but is also visually and texturally appealing. The influence of vision on flavour has been empirically tested; for example the effect of colour—be it the colour of the food itself [130], or the colour of the plate and tableware [61, 62] is known to greatly influence the feeding experience (for a review see [129]). The sound a food makes in the mouth is also important in our overall liking [147]. We will return to this idea of multisensory experience in nourishment when we discuss taste and smell perception in blind individuals (Sect. 4.4). It is already clear, however, that multisensory integration is a crucial aspect of the human experience and is closely linked to many survival responses.

3 Multisensory Areas in the Brain

In this section we review all the classical multisensory areas of the brain. We argue that these multisensory areas are crucial for the development of body reference frames and spatial representations, for interacting with objects, accomplishing complex motor movements, and for determining one's self-representation within the world. These brain areas are capable of integrating information from multiple modalities, rather than only a specific sensory modality. We argue that these areas are organised according to functional specificity and combine multiple input sources to create an amodal reference frame.

The **posterior parietal cortex (PPC)** has been identified as an important multisensory area within the brain, converging visual, auditory, and tactile information for planning and executing movements. The PPC appears to be important for reference frame transformations between the senses [19]. For example, when we hear something, the perceived sound is encoded according to head-centred coordinates (because our ears are fixed on the head). In order to look at the source of the sound, its location needs to be coded in an eye-centred frame of reference (relative to the current eye position). Lewald and colleagues suggested that the PPC relates azimuth angles of sounds to body coordinates, in order to convert the information to different modality-specific reference frames [83]. To make a hand movement to the seen/heard object, it would then need to be coded in a hand-centred reference frame. Rather than undergoing arduous computations each time we move towards a sensed object, the PPC appears to maintain a common eye-centred reference frame, modulated by eye-, head-, body-, or limb position signals [26]. Indeed, even a touch on the arm appears to be coded in the common eye-centred reference frame [59, 60, 109]. Further evidence of that the PPC is involved in integration comes from studies using brain stimulation. Transcranial magnetic stimulation (TMS) over this region disrupts multisensory visual–tactile integration [101], while transcranial direct current stimulation (tDCS) over this area enhances multisensory spatial orienting [14]. A common multisensory reference frame would facilitate communication between the modalities (with regards to spatial location) and the PPC is, therefore, considered an important multisensory area in the brain—particularly in spatial coding, though it may also play a role in temporal perception [152].

The **anterior intraparietal sulcus (aIPS)**, from the postcentral to the superior parietal sulcus, is another known multisensory brain area with a particular role in the integration of visual and haptic signals (for a review, see [64]). For example, multisensory location information is needed to reach towards and pick up an object that is *seen* on the table. Current understanding is that the proprioceptive knowledge of the hand converges with the visual information for hand position in this area of the cortex. While the posterior IPS and some visual areas (discussion to follow) represent the hand in a predominantly visual manner, the aIPS converges multisensory information (vision and an important proprioceptive contribution) to build hand position representations for peripersonal hand space [50, 89].

The **superior temporal polysensory (STP)** region, in the posterior bank of the superior temporal sulcus (STS), has been a labelled as and "association" area because it receives auditory, visual, and somatosensory stimulation and is composed of unimodal, bimodal, and even trimodal neurons [18]. Its receptive fields are generally large, including both visual fields and bilateral somesthetic and auditory receptive fields [65]. In particular, peripheral vision and motion perception appear to be supported by projections from the STP and STS to the primary visual cortex [41]. These parietal areas project to primary visual cortex (V1 and V2) [117]. This same region, but a little higher at the temporoparietal junction (TPJ), has been demonstrated in humans to be responsive to visual–tactile stimulation [68]. Once again, this multisensory cortex is associated with spatial perception—more specifically the feeling of being localised at a position in space, from a first-person perspective [13].

The **anterior Ectosylvian Sulcus (AEC)** in cats is an important anatomical area because of its wealth of cortico-cortico as well as cortico-subcortical projections. In many cases, neurons in the AEC respond to multisensory stimuli [96, 113]. In one of the first studies to demonstrate trisensory neuronal response (Fig. 2), Jiang and colleagues reported that of the cells in the AEC, recorded with the single-unit technique, ~60% were unimodal, ~30% were bimodal, and ~10% were trimodal [71].

Depending on how multisensory neurons are defined, or tested, some studies report as much as 66% of neurons in the AEC to be multisensory [35] with projections to the SC, which likely underlies the latter's multisensory nature [70, 71]. While neurons in the SC always demonstrate maximum enhancement when their unimodal discharges overlap [143], the relationship in the AEC appears to be more complex. While some neurons in the AEC prefer auditory stimulation to precede the visual stimulation, other neurons have peak responses when the auditory stimulus trails the visual by as much as 200 ms [70]. Each neuron appears to have a preferred temporal relationship between stimuli (see also [11]). Moreover, depending on the temporal interval between the modalities, the same neuron can be excitatory or inhibitory [70].

Given the already multisensory nature of this region, cross-modal plasticity following sensory deprivation might be expected, where visually specific neurons

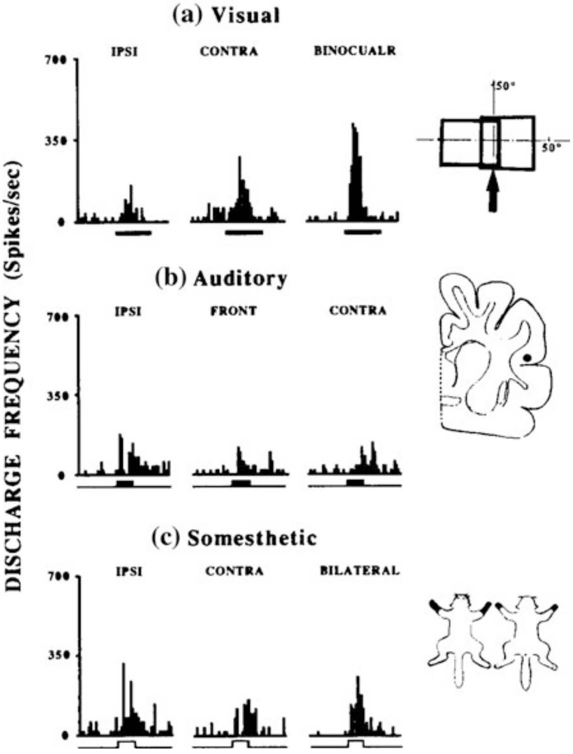

Fig. 2 Responses of a trimodal unit to a visual (**a**), an auditory (**b**), and a somatosensory (**c**) stimulus. Visual stimulus: a light bar (3° × 10°) moving upwards through the RFs at a speed of 300°/s; somatosensory stimulus: an air puff (100 ms); auditory stimulus: a burst of white noise (100 ms, 70 dB). *Black bars*, visual stimuli; *thin line with filled bars*, auditory stimuli; "*up bars*", air puff stimuli. Binwidth 10 ms. *Insets* show positions of RFs. The *black dot* in the schematic coronal section of the cat's brain represents approximate position of the cell within anterior ectosylvian cortex. Adapted from [70], Copyright (1994)

may become responsive to stimuli in other modalities after a lack of visual stimulation. Indeed, a significant cross-modal plasticity of the AEC was observed in cats that were visually deprived at birth [114]. Areas that were normally visual (the ventral bank and fundus of the AES) underwent a cross-modal intrusion, becoming primarily responsive to auditory and/or somatosensory stimulation.

These results in the cat provide a model for the intermodal compensatory plasticity that is observed following sensory loss; an area that is primarily visual, but demonstrates some measure of integration of auditory and somatosensory information with vision, will undergo considerable plasticity when vision is not available, becoming more responsive to auditory and tactile stimuli. Multisensory areas therefore *allow* for cross-modal plasticity following loss of a particular sensory modality. This transition from bimodal (or trimodal) into unimodal (or bimodal) specificity is likely mediated by GABAergic neurons [36], with a corresponding expansion of the remaining unisensory receptive fields into the area previously occupied by the modality that has been eliminated. Thus, the cross-modal abilities following sensory loss are maintained and strengthened, rather than completely novel. Following up on this point, the subsequent sections of this chapter will discuss cross-modal abilities in cortical areas that are traditionally considered unisensory.

4 Primary Visual Cortex

Visual information from the retina is projected from the eye through the optic tract (including the optic chiasm) to the Lateral Geniculate Nucleus (LGN) before arriving to the occipital cortex. Neurons in this part of the brain, combined with other neurons ‘devoted’ to vision throughout the cortex, are said to take up about 30% of the cortex [54]. In comparison, approximately 8% of the cortex is estimated to be devoted to tactile information processing, and 3% for auditory processing. What, then, happens to these neurons when vision is restricted or completely eliminated? Over the last ten years, neuroimaging studies have demonstrated a considerable amount of neural plasticity in the “visual cortex” of blind people. This plasticity has been used to explain the superior abilities of blind people in auditory, tactile, proprioceptive and motion tasks (for a review, see [82]). We propose that this plasticity potentially arises from the presence of multisensory neurons within the primary visual cortex. These neurons would remain latent and largely immature in the normal “visual” brain, but would become active in the blind brain as a result of the absence of visual input.

4.1 Auditory Activation of Visual Areas

Auditory stimuli have repeatedly been demonstrated to activate the visual cortex in early blind (EB) individuals, but not necessarily in sighted controls. The initial findings that EBs have neural activity within the occipital cortex was a novel insight and an explanation for anecdotal evidence of heightened auditory abilities in blind people [33, 144]. Several studies have demonstrated superior performance of EBs in auditory tasks as compared to sighted controls (SC), which has been attributed to an increased metabolic activity in the visual cortex of CB during the performance of these auditory tasks [6, 122]. Sensory substitution devices (SSD), such as the PSVA (prosthesis substituting vision with audition), have also been used to demonstrate the fact that auditory stimulation can activate the occipital cortex [34]. The activity in the “visual cortex” is critical for interpreting the auditory information from PSVA devices [28], for localising simple sounds [27], and for interpreting auditory motion [106]. Moreover, the activation of the visual cortex from auditory stimulation led to the functional specialisation hypothesis [29], which suggests that the occipital cortex is specialised for spatial processing—rather than being strictly associated to visual processing (this will be further discussed in Sect. 6). While this plasticity in blind people is remarkable, and can be used to explain their often superior auditory abilities, activation of the occipital cortex by auditory stimuli is not always dependent on visual deprivation.

Auditory stimuli can activate the visual cortex, even in a brain that developed “normally” (see review in [52]; Fig. 3). Half a century ago, studies in the cat demonstrated that as many as 41% of “visual neurons” also responded to auditory stimuli [97]. In support of the functional specialisation hypothesis, these multisensory neurons in the visual cortex were thought to be spatially specific [97]. With spatially and temporally precise neuroimaging techniques, a recent study has confirmed that auditory stimuli evoke spatial-specific activity in the visual cortex of normally developed sighted individuals [17], even in the absence of simultaneous visual stimuli. The activation of the visual cortex by auditory stimuli is likely to originate from early projections from the auditory cortex and the superior temporal sulcus (STS) [117].

Taken together, we can conclude that a pathway for auditory stimuli to the occipital cortex is present even in brains that have developed with visual input. While these pathways are not completely pruned over the course of normal development, they remain largely undeveloped. These multisensory connections appear significantly strengthened and have expanded cortical representation when visual input is unavailable, for example in the blind brain, and become apparent following training and experiences with non-visual stimuli [29].

4.2 Tactile and Proprioceptive Activation of Visual Areas

In the same vein as auditory stimuli, tactile devices that provide a complex touch stimulus also activate the visual cortex in blind people, but not necessarily in sighted controls. For example, in addition to somatosensory cortex response, blind people's occipital cortex is activated during braille reading but not for simple tactile detection tasks [124]. This activation appears to be critical for interpreting and understanding the tactile Braille stimulus, since Braille reading is impaired when the occipital cortex is damaged [57] or disrupted with TMS [25]. While reading was impaired, simple tactile detection was not when TMS was applied to the occipital cortex [25], but tactile detection was disrupted when TMS was applied to the parietal cortex [58]. Therefore, the visual cortex is actively involved in the representation of Braille letters, but not their detection. It could, thus, be argued that the visual cortex is actively involved in an amodal representation of text. The fact that text is represented in such an amodal fashion could explain why the visual word form area (VWFA), located within the visual cortex (in the ventral visual stream), is activated when blind individuals read a braille text (tactile) and when sighted individuals read a visual text [116].

Early blind people who are trained with the tongue display unit (TDU) also activate the occipital cortex when determining the orientation of a letter presented with the device [112] (Fig. 4a). Moreover, activation of the visual cortex, using TMS stimulation, induces phosphenes in sighed controls but refereed sensations on the tongue of practised TDU users [79], and tactile sensations in the fingers of practised Braille readers [110] (Fig. 4b). The activation of the occipital cortex during both Braille reading and TDU tasks in blind people is thought to be a result of the fact that these tasks demand a high degree of spatial acuity—they are both spatial perception tasks. The spatial layout of the neurons in the occipital cortex

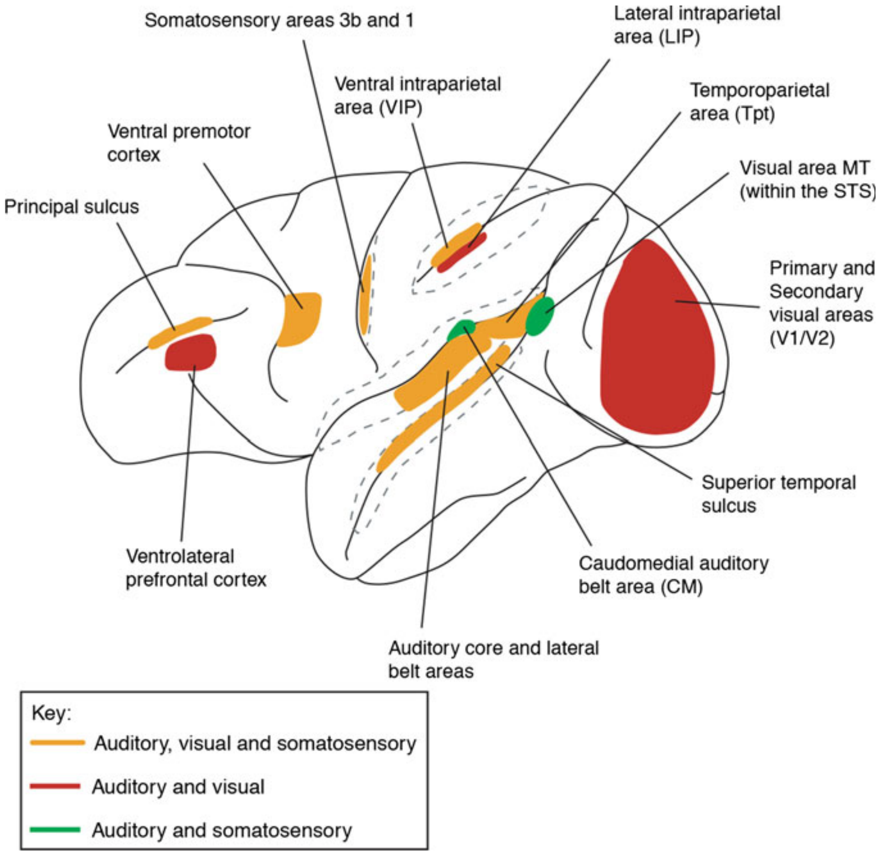

Fig. 3 The more modern scheme of the cortical anatomy of multisensory areas. *Coloured areas* represent regions where there have been anatomical and/or electrophysiological data demonstrating multisensory interactions. In primary and secondary visual areas (V1 and V2), the multisensory interactions seem to be restricted to the representation of the peripheral visual field. *Dashed gray outlines* represent opened sulci. Reprinted from [52], Copyright (2006), with permission from Elsevier

enables the development of a retinotopic map, which provides vision with a high degree of spatial acuity. The particular characteristics of the neurons in this region appear to be an important factor for its recruitment in non-visual spatial tasks during blindness.[1]

Under some conditions, early visual impairment appears to lead to better tactile performance in blind people as compared to sighted controls, as discussed in [82]. For example, in the "crossed hands paradigm", where people cross their arms and

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[1] Further discussions on cross-modal plasticity elicited by the stimulation of the tongue (TDU), and amodal representation of space, can be found in Chap. 6 by Chebat et al.

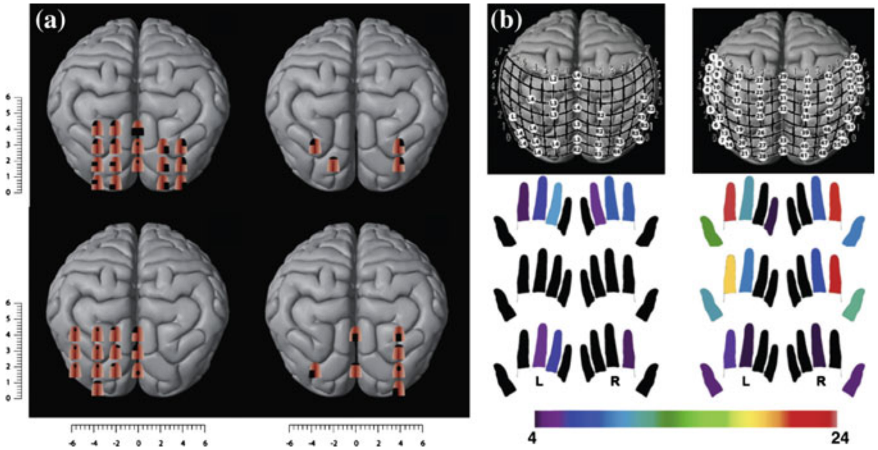

Fig. 4 TMS of the visual cortex in congenitally blind subjects can induce tactile sensations. **a** Somatotopically organised tactile sensations in the tongue induced by TMS over occipital cortex in four blind subjects who were trained to use their tongue to perform a motion discrimination task. The figure shows the areas of the tongue where tactile sensations were felt (indicated in *black*) after TMS stimulation of the occipital cortex. The *numbers* on the scales refer to the distance (in cm) from the inion. **b** TMS-induced tactile sensations referred to the fingertips in two congenitally blind proficient Braille readers. The number of visual cortex sites from which paresthesiae could be induced in a particular finger is colour-coded (see colour map), with *red* indicating the highest number of cortical sites that induced paresthesiae in a particular finger and *purple* the lowest number. Reprinted from [82], Copyright (2014) with permission from Elsevier

then have to determine which hand (left or right) was touched first, early blinds outperform sighted people [120]. Sighted people typically have difficulty determining which hand was touched first but blinds can report the temporal order of touches equally well with their hands in any posture. These results support the hypothesis that when vision develops normally, touch on the body is coded in a visual reference frame [59], both for perception and to guide actions [60]. The visual reference frame is an externally defined coordinate system that is automatically used by sighted controls. Blind people, on the other hand, only use an externally defined coordinate system when specifically instructed [94, 95]. Thus, guiding actions towards external objects is based on an external reference frames in sighted, but is based on an internal reference frame in blind people [118]. Much like the visual system, online corrections for hand orientation are made with proprioceptive inputs in the blind [55]. In addition to the increased neural plasticity in the blind brain, the ability of blind people to use either reference frame can also partially explain certain behavioural advantages compared to sighted controls.

The cortical networks associated with movement control are fairly similar for sighted and blind people, leading researchers to conclude that a multisensory network develops with a sensorimotor feedback system, rather than a visual feedback system [42]. While visual feedback primarily supports the system in adults with normal visual development, they hypothesise that such a system originates from a multisensory framework. Thus, this same network can be used regardless of the modality feeding the system in people with sensory deficits. Similarly, several perceptual tasks have demonstrated the role of the occipital cortex in decrypting highly spatial, non-visual information. While the visual cortex is shown to be active when blind people, but not sighted controls, are highly trained in tactile tasks [112], there are now a handful of studies that demonstrate exceptions to this rule, even for certain simple tactile stimuli.

Despite popular belief, the occipital cortex can be recruited for tactile spatial tasks even in people with intact visual systems [148]. In this study they demonstrated that applying TMS to the occipital cortex disrupts tactile orientation discrimination (a spatial-based task) but not the ability to detect the stimulus, or to perceive texture (detection or discrimination tasks). Further, a subregion of the lateral occipital cortex, known as the lateral occipital tactile–visual area (LOtv) is activated by tactile stimuli (see discussion in [64]), for both 3D haptic perception [5], and less complex haptic stimuli [74, 108]. It remains a controversial point whether the activity in the LOtv represents amodal shape perception [5], or is attributed to mental imagery [149]—which can also be amodal (see Sect. 6.2). As was suggested for auditory-based studies, the multisensory cortical connections in the occipital lobe likely underpin the activity in the occipital cortex of blind people elicited by tactile stimuli; these stimuli likely become transduced into amodal representations in the multisensory blind brain.

4.3 Pain Activation of Visual Areas

The relationship between vision and pain is well known, even intuitive [63]. We almost always look at the site of injury, and what we see will gauge our response. If the skin appears unharmed there is a “visual analgesic” effect and we feel less pain. If the skin is broken and bleeding, we will have an increase in pain perception. Experimentally, the effect of short-term visual deprivation (one week), causes otherwise normal people to experience increased tactile and thermal acuity [153]. This early empirical data also demonstrated that blindfolding causes a drop in heat pain thresholds, indicating that lack of vision is related to hypersensitivity to pain.

In our pioneering study of pain and temperature perception in a blind population, we demonstrated that blind subjects had significantly lower heat pain and cold pain thresholds than matched controls [127]. We demonstrated that hypersensitivity to pain is specific to noxious thermal stimulation, rather than to thermal stimulation in general, and the effect is not culturally based. Taken together with findings of augmented responses to threatening auditory stimuli in blind subjects [75], these data provide compelling evidence that early blindness might cause an increased attentiveness to external threats.

In order to determine if the hypersensitivity to threatening stimuli arises from a compensatory neural plasticity that is rooted in the critical period of development, we compared the pain sensitivity in early and late blind subjects. While early blind individuals were quite different, data from late blind subjects was very similar to that of sighted individuals, including both responses to painful heat stimuli and questionnaires assessing awareness and anxiety towards pain [126]. This suggests that visual deprivation, per se, does not alone determine the development of pain hypersensitivity—the time at which the visual system is deprived is equally important.

Two competing hypotheses have been proposed to explain pain hypersensitivity in congenital blindness [126, 127]. According to the first hypothesis, pain hypersensitivity reflects cross-modal plasticity of brain circuits as a result of the lack of visual input. The absence of inhibitory effects of vision on pain perception in the visually deprived blind brain (i.e. a lack of inhibitory feedback from the visual analgesia effect) might leave the neural circuitry associated with nociceptive inputs particularly sensitive [86, 87, 153]. Alternatively, a second hypothesis suggests that the pain hypersensitivity results from a hypervigilance to threatening stimuli in early blind individuals. Vision, when present, can signal potential threats to the body (e.g., a red hot stove) so that individuals can remain carefree until they see a dangerous stimulant. In the absence of the visual warning function, blind individuals might instead adopt a chronic state of hypervigilance as a way to avoid tissue damage. This more integrative interpretation of the pain hypersensitivity, combining both the psychological and biological aspects of pain, can also account for the observations that early blind individuals show increased responses to auditory threats [75], and are better at identifying body odours with a negative emotional valence [69]. Indeed, as shown in recent brain imaging studies, salient visual and noxious stimuli activate a partly overlapping cortical network [98], supporting the hypothesis that there is an intricate integration of vision and pain processing.

4.4 Chemical Senses

The relationship between vision and taste is often automatic. Chefs will naturally devote significant amounts of time making their food look good, in addition to making it taste good. There is also empirical evidence that colour affects flavour perception [61, 62, 130].

Behavioural evidence has demonstrated that EB is associated with increased odour awareness [9] and increased ability to correctly name odours from everyday life [32, 99, 123]. We have replicated this enhanced detection of odours when blind participants sniffed the odorants (orthonasal route), but when they smelled them retronasally (through the mouth) the sighted controls tended to outperform the blind participants. Similarly, blind people appear to have a reduced taste sensitivity [47].

There are a few studies that have investigated the neural plasticity and behavioural differences associated with smell and taste in blindness (see review in [48]). BOLD responses recently demonstrated the important difference between taste and smell in blindness. While odours activate the visual cortex in blind participants, but not sighted participants [78], taste processing does not demonstrate this multisensory plasticity [49], see discussion in [81]. These studies have suggested that experience with food is an important predictor of performance in chemosensory experiments.

In the absence of vision, blind people face several obstacles when searching for food, buying food in impervious packaging, preparing food, and eating in restaurants [12], which might limit the diet of many blind people. While their diet may be limited, their exposure to odours is not, since most odours are not food-related. The limited variety in a blind person's diet would provide them with fewer flavour experiences causing poorer sensitivity to stimuli presented through the mouth, but normal (or heightened) sensitivity when stimuli are sensed orthonasally. Thus, the difference of experience between taste and odour appears to underlie the neural activation and behavioural performance differences reported between blind and sighted controls [48].

5 Primary Auditory and Somatosensory Cortex

In addition to the mounting evidence presented above of other sensory modalities activating the primary visual cortex, here we present evidence of the reverse—visual, and other types of stimuli, activating the primary auditory and somatosensory cortices in sensory deprived and normally developed brains.

In the auditory cortex, despite it being primarily an auditory processing centre, single electrode recordings have demonstrated the presence of trisensory neurons, responding to auditory, visual, and somatosensory stimuli [45]. This multisensory facilitation in the auditory cortex appears to be particularly responsive to voices and faces [22, 105, 139], i.e. multisensory integration for communication [52]. These multisensory neurons for communication are more likely to be enhanced when audio-visual delays are short, whereas longer delays between stimuli are associated with response suppression [51]. These neurons, therefore, support the hypothesis that temporal proximity is an important modulator of the activity in multisensory neurons. In addition to communication, multisensory neurons in the auditory cortex also play an important role in eye positioning [46, 146], and somatosensory processing [72]. Further, these multisensory pathways within the primary auditory cortex are present even after normal auditory development. However, as was the case for blind processing, these multisensory pathways appear to be particularly well developed in deaf individuals, as evidenced by cortical plasticity, and may underpin the selectively enhanced visual abilities of the deaf [8, 85].

Similarly, the primary somatosensory cortex is also responsive to non-tactile stimulation, in particular auditory and visual stimulation. Multisensory convergence on a single neuron in the somatosensory cortex has been demonstrated through single-unit recordings [150, 151], and tracer studies [23]. These kinds of multisensory neurons would likely support the cortical plasticity associated with early somatosensory deprivation [53].

In somewhat of a resistance to accept multisensory activity in primary cortices, this was thought to occur only *after* the stimuli had been processed in multisensory regions (presumably after an initial processing in the unisensory areas). That is, evidence for multisensory convergence in the "unisensory" cortices was thought to be the result of "top-down" feedback from multisensory areas to the primary sensory areas [21, 38, 88, 102]. However, tracer studies have shown direct projections of auditory neurons to V1 and V2 [117]. In addition, damage to higher order "multisensory regions" does not necessarily hinder multisensory integration abilities (for a review see Ettlinger and Wilson [40]). Further, the timing of some integration activity (occurring 40 and 50 ms after stimulus) are too early to arise from feedback pathways [43]. Thus, multisensory activity in the primary sensory cortices results from a combination of feedback, feedforward, and lateral connections [43].

6 The Amodal Cortex

It is now becoming particularly clear that the view of a modality-specific divided brain is inappropriate, or at least incomplete. Although this might mostly hold true of primary cortices, where only about 10% of neurons respond to "inappropriate sensory" stimuli, even the boundaries of these divisions are unclear (i.e. multisensory [142]). Instead of sensory delineations, sensory deprivation studies have suggested a functional delineation for certain cortices [3, 136]. For example, the motion sensitive middle temporal cortex (hMT+) responds to any kind of motion, be it visual, auditory, or tactile in origin, and this is true for both sighted and blind individuals [91]. A common hypothesis suggests that the occipital cortex is, thus, spatially arranged, providing spatial information regardless of the modality (for a review see [125], see also Chebat et al., Chap. 6).

While vision might be used to localise objects for sighted individuals, auditory and proprioceptive localisation cues are utilised by the blind [145], and as such, both might rely on the same brain areas to interpret spatial information. In particular, the retinotopic arrangement of the visual cortex seen in sighted individuals is maintained in blind individuals when this cortical region is recruited for tactile tasks, conserving a topographic representation of space [79, 110], see Fig. 4. Visual experience is, therefore, not a mandatory prerequisite for the topographically organised, functionally related, representations in the extrastriate visual cortex—these appear to be supramodal neural response patterns in the human brain [80]. In the same vein, the dorsal stream appears to be shaped by non-visual spatial information during early development [42].

Theoretically it is easy to fathom that the representation of spatial information in the brain is amodal: the structures supporting mental and spatial representations in the blind and sighted are often the same and the cortex maintains its functional organisation despite the absence of vision from birth. Demonstrating such a thing is very difficult, however. For example, auditory activation of the "visual cortex" can be interpreted as an attentional recruitment by auditory stimuli rather than attributing the activity to the auditory stimulus (e.g. [24, 84]). Similarly, in the case where a sound of a dog barking activates the visual cortex, the classic criticism has been that the sound invokes imagery, and the imagery is what then activates the visual cortex. Since all modalities can initiate mental imagery, might imagery be amodal?

6.1 Amodal Imagery

While imagery is a highly visual construct in normal-sighted individuals, mental imagery also expands to the other sensory modalities [76]. In this more broad use of the term, mental imagery refers to the construct or representation of a quasi-perceptual experience in the absence of perceptual sensory input. It is also commonly referred to as “seeing with the mind’s eye”. Thus, imagery refers to a particular aspect of memory in which a mental “image” of a stimulus is maintained. Various neuroimaging studies have demonstrated that mental imagery activates similar neuronal patterns as processes related to sensory perception. For example, visual imagery will activate the visual cortex, particularly the extrastriate and associate visual cortices; while auditory imagery will be associated with the activation of secondary auditory cortices [76].

Mental imagery in the blind appears to be a construct of the remaining sensory modalities. While blind people have limited mental imagery capabilities restricted to non-visual modalities, they often outperform sighted individuals in mental imagery tasks. For example, Paivio and Okovita [100] found that congenitally blind people were better than sighted individuals at recalling item pairs with a high-auditory imagery component, whereas the inverse was found for items with a high-visual imagery component [100]. Moreover, as imagery has been shown to facilitate encoding, learning and memory recall, Marchant and Malloy [90] demonstrated that congenitally blind and deaf individuals were able to recall as many paired words as sighted control individual, when these words contained multi-modal imagery (e.g. a train) [90]. More specifically, recall was only impaired for congenitally blind individuals when items possessed unimodal visual imagery (e.g. a rainbow). As such, the mental imagery of blind individuals is limited to, but also compensated by, non-visual sensory modalities. Moreover, some particularities of object representation that, in sighted individuals, are strongly visual-based, such as shape, contours and textures, are acquired in the blind through the other modalities, such as touch. Vision is, therefore, neither necessary nor sufficient for mental imagery, and as such can be equally experienced even by early blind individuals.

Mental imagery in the blind may also be limited to sequential processing, as simultaneous processing is thought to be purely visual [141]. This recent revelation might partially explain the impaired performance (i.e. slower response times) of blind individuals in some, but not all, visuospatial imagery tasks [2, 73, 141].

Therefore, although mental imagery is possible, even when reared in the absence of visual input, it is limited to non-visual sequential imagery.

In support of the amodal mental imagery hypothesis, the visual cortical areas are activated when blind people perform mental imagery tasks. For example, the ventral stream is known to play an essential role in object representation [56, 138] and, consequently, is an important locus for imagery. In sighted individuals, the occipitotemporal (OCT) cortex of the ventral stream seems to be equally active for visual and haptic shape representation [4, 5, 77, 104]. Although sighted individuals can resort to visual characteristics of the stimulus for mental shape representation, blind individuals can also generate a mental image of an object's shape through tactile sensory information. A recent study by Peelen et al. [104] demonstrated that, in the blind, the OCT cortex, and particularly the object-selective cortex (OSC) is active during tactile shape mental imagery, prompted by having blind people think about and compare the shape of different objects [104]. Object representation was prompted by a verbal (auditory) stimulus, by which the name of a common object was given. The activation of the OCT in both sighted and blind individuals, for visual and tactile shape processing, supports the notion that this cortical area is associated with amodal shape representation [111].

Likewise, the dorsal stream, associated with spatial localisation, also plays a role in imagery, particularly in imagery of visuospatial information. As revealed through studies in the blind, this cortical stream is associated with amodal spatial processing; spatial imagery prompted from verbal instructions has been shown to activate parieto-occipital areas of the dorsal stream in both blind and sighted individuals [16, 140]. Similarly, in an experiment where participants discriminated and compared the size of the angle between a clock's hands, blind and sighted participants both activated the posterior parietal cortical areas [16]. Thus, both the dorsal and ventral streams (see Fig. 5) normally associated with visual imagery also have a supramodal functional nature and are recruited for tactile and auditory mental imagery.

In summary, findings suggest that the multisensory plasticity following blindness extends beyond sensory perception, to processes of mental imagery. While there are some limitations in the imagery capabilities of the blind, namely the absence of certain, purely visual, characteristics (e.g. colour), and their inability to perform simultaneous processing of mentally generated images, blind people often outperform visual controls in non-visual mental imagery tasks. These multisensory processes suggest that it is possible that different forms of mental imagery can be represented simultaneously in the brain.

6.2 Amodal Memory

Although mental imagery refers to a particular aspect of memory, memory encompasses various other dimensions, including declarative, semantic, episodic, and procedural memory. Early blindness seems to result in an advantage for many

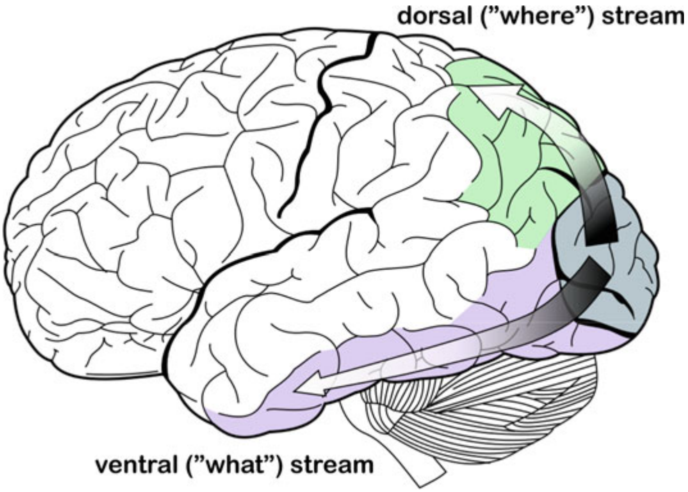

Fig. 5 The dorsal stream (*green*) and ventral stream (*purple*) are shown. They originate from a common source in the primary visual cortex. Modified by Selket from *Anatomy of the Human Body,* Gray H, Fig. 728 (1918)

of these aspects of memory leading several researchers to conclude that the primary visual cortex is recruited for higher order cognitive processes, such as verbal memory. In blind individuals, while the anterior region of the occipital cortex is associated with Braille reading, the posterior region is active during verbal memory and verb generation tasks [6]. It has been suggested that, in the absence of visual input from birth, the typical visual system hierarchy is inverted: in the blind, extrastriate areas become associated with amodal (or multisensory) processing, while the primary "visual" cortex is recruited for processing higher order cognitive functions, such as verbal memory [3, 6].

Verbal memory tasks yield different activation patterns for blind and sighted controls. Comparative BOLD fMRI measurements have revealed that, while the primary visual cortex is active during verbal memory and verb generation tasks in blind individuals, this activation is absent in sighted controls [6]. Furthermore, the magnitude of V1 activation is strongly correlated with verbal memory performance in blind participants [6]. Similarly, disrupting activity in the occipital pole by application of rTMS induces greater errors—particularly semantic errors—in an associative verb generation task in blind but not sighted individuals [3]. These results, thus, further support the role of the visual cortex in verbal processes of early blind individuals (see also auditory verb generation [20], speech comprehension [121], and language processing [10]). The visual cortex is not reserved for low-level visual processing, it can also be critical for processing higher order cognitive functions. Furthermore, in a follow-up study, long-term recall performance was assessed by recalling blind participants one year after initial testing, and retesting them with the words used during the initial verbal memory tasks [115]. Raz and colleagues reiterated the correlation between activation in the occipital cortex and performance in verbal memory. The occipital cortex also plays an active role in episodic and semantic memory processes in early blind people.

More generally, memory capacity and fidelity appear to be enhanced with early visual deprivation. Blind individuals, particularly early blind people, are often reported to have superior memory [6, 67, 103, 107, 119, 128, 137]. Moreover, superior memory abilities associated with blindness depend on both the degree and timing of the visual impairment [67]. While memory appears to not be different between the late blinds and sighted individuals, it is considerably better in early blind populations [103]. Early blind individuals were found to, not only report more correct words (words from the original list), but also report fewer "false memories" (words that were semantically similar to, but not part of, the original word list) and fewer unrelated words [103]. This enhancement in memory suggests that blind individuals may rely more heavily on working and episodic memory in the absence of visual input.

7 Conclusions

While it was originally thought that the brain was parcelled into several specific subregions, each responsible for interpreting the information from a given sensory modality, along with a few "multisensory" areas that work to combine information across the senses, this idea has been largely debunked. A more recent view of the brain suggests that, instead of being sensory specific, cortical regions are functionally specific, likely based on their neuronal arrangement (e.g. striate cortex is best for interpreting spatial information, while the LOtv interprets shapes). Much of the evidence for non-visual activation of the "visual" cortex has come from blind individuals who demonstrate considerable multisensory neural plasticity. Blinds trained in tactile and auditory tasks or on high-tech devices recruit their visual cortex to interpret the complex material. While this now classic example of neural plasticity was surprising and confusing at first, it fits with the evidence from several papers demonstrating that, even under normal visual development, activity in the occipital cortex can be elicited from tactile, auditory, olfactory, pain, and proprioceptive stimulation. Thus, the multisensory circuitry to the visual cortex is fastidious but certainly present, and becomes particularly robust when visual development is irregular.

Perhaps, vision plays a pivotal role in establishing multisensory functions during ontogeny, which would explain why visual pathways extend across to nearly all areas of the brain [66]. Vision, during development, might calibrate the senses to each other (so that size can be understood visually or haptically; so that speed can be understood visually and auditorally, enabling reference frame conversion between the modalities, etc.). In conditions of poor vision, the senses would be calibrated by another modality. Thus, while multisensory cortical areas have the primary role of integrating information, the evidence of multisensory activity in primary sensory cortices might be primarily related to the role of vision in ontogeny. After normal development of the senses, vision would be less relevant for primary cortical functions, and should eventually be pruned.

Understanding the multisensory nature of the brain enables us to develop better rehabilitation schemes and technologies. Rehabilitation schemes following brain damage (e.g. stroke related) have already benefitted from the knowledge of automatic audio–visual interactions when performing visual search tasks [15]. Moreover, understanding the role of vision within the brain, and the extensive plasticity in the blind brain, can improve technologies built for the blind. Sensory substitution devices are developed with the knowledge that objects can be represented in multiple senses. These same devices can be further improved with a better understanding of the multisensory blind brain. Rather than devices that represent vision, we must remember that vision is in itself a representation of the outside world. The kinds of information that could enrich blind people's environments do not necessarily have a strictly "visual" component. Instead, thinking about the amodal functions of the occipital cortex might provide insight into the technological developments that should be pursued in the future.

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On Spatial Cognition and Mobility Strategies

Edwige Pissaloux and Ramiro Velázquez

1 Concept of the Spatial Cognition

Spatial cognition is a fundamental and vital property of human knowledge (and behavior) which provides means to interact with space once it has been perceived and its structure has been understood.

Since the seminal works of Hein and Held [1], it is known that spatial cognition is acquired pro-actively, i.e., by the physical experience of space interaction, notably by mobility in the space.

Sometimes, instead of “mobility,” the terms “navigation” or “way finding” are used by abuse of the language.

Initially, the term “navigation” was used to express someone’s capability to find his/her own way while navigating on the sea between two points located far away from each other.

By extension, some authors [2, 3] use the word “navigation” as the capability to find the way on the earth and in the air while intentionally keeping the planned trajectory from point A to B.

However, the mobility is a complex cognitive task, and vital for all; it encompasses navigation, but also requires to keep the posture, to orient oneself in space, to know the socio-urban organization, to update the current path because of the unscheduled and unexpected events, etc. For example, moving from your own home to work, includes more elementary tasks such as (1) the constant orientation toward the target location (with respect to your current spatial position), (2) the constant judgment of the traveled distances, (3) the constant check if you are

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following the correct path, (4) the constant avoidance of obstacles, (5) the memorization of all this information, so the return trip is possible, (6) the verification if reached and expected targets correspond to each other, etc.

The spatial knowledge is a key element for the quality of life.

This knowledge may emerge from the possible interactions between specific types of sensory data and the interactions of the cognitive strategies involved in the spatial mobility inside small, medium and large-scale environments [4–6] (personal, near, and far spaces).

The rest of the chapter is organized as follows. Section 2 briefly discusses the current state of art on sensory data which seems to be involved in space perception emergence, while the Sect. 3 discusses the movement perception and spatial navigation. Section 4 outlines some neural evidences of spatial cognition. Section 5 addresses some findings of spatial cognition in animals. Section 6 recalls some of the most popular models for spatial knowledge structuring. The concluding Sect. 7 encompasses some open questions of spatial knowledge of visually impaired people (VIP).

2 Sensory Information and Perception of the Movement

Several heterogeneous sources of sensory data lead to the perception of the space (the environment) and to the experience of travel. These data come from the navigable space (such as vision data) and from body's motion ego-perception (such as proprioceptive and vestibular data) which occur during the interaction with space via the navigation.

2.1 Vision Data

The investigations on the interplay between visual data and mobility are usually spread in two categories: optic flow and visual cues/clues/landmarks.

2.1.1 Optic Flow

The human retina is stimulated by a reflected light generated by a given location in the space. During the navigator's motion in space, the image of the location on the retina moves as well. The dynamic relationship between the navigator and the visual motion of the object is called "optic flow" [6, 7]. For Lee [8], the visual perception starts with optic flow.

Optic flow plays several functions during the mobility:

(1) it allows the estimation of distances from the viewed objects;
(2) it allows 3-D object recognition (frequently from their shape) [9], without any additional information from the vestibule [10];
(3) it allows to implement the simple navigation strategies such as path integration [11, 12];
(4) it controls the posture during mobility [13, 14], and the posture adaptation during the obstacle avoidance or body-motion alteration [15–17]. In experimental conditions, where the optic flow is the sole environmental data available to the navigator, the modification of the optic flow can modulate the mobility behavior without destabilization of the navigator's movement [18].
(5) it enhances the perception of the body motion [19, 20] and of the position of the head during the movement [21].

However, the knowledge of the optic flow alone does not guarantee the precise estimation of distances and orientation during the mobility [22]. The traveled distance underestimation is a basic error is such case [23].

The optic flow data in combination with other visual indices (visual cues/clues/landmarks) can lead to accurate ego-motion perception and correct estimation of the ego-distances, which are fundamental for safe mobility [24]. The combination of optic flow and distal vision cues or landmarks increases the reliability of ego-motion cues estimation (self-rotation and heading direction toward distal goals), but does not reduce the error of the distance underestimation [21].

2.1.2 Importance of Visual Cues/Clues/Landmarks

Near and far static specific objects, which may be perceived with sight, are named, respectively, visual cues, visual clues, and landmarks. Visual clues are the mobile visual cues, while landmarks are visual objects which may be perceived from almost any place of a large space. In the remainder of this chapter, and par abuse the language, the word "cues" will designed three categories of objects; cues, clues, and landmarks.

All cues, once occurred in the visual field can be used as references while traveling in the space. Despite of the fact that optic flow is a fundamental source of the data for guidance and motion anticipation, the available visual cues have several important roles during the mobility [25].

The main results on the importance of visual cues are recalled hereafter.

First of all, visual cues significantly increase the stability and control of balance [26] whenever visual cues are perceived in central or peripheral retinal field [27]. For example, Azulay et al. [28] reported that the Parkinsonian subjects improve significantly their ability to move steadily and continuously if the visual strips were integrated on a featureless floor because their vision has more data to provide to the balance system. Philbeck et al. [29] found that even very short (instant) perception of cues may significantly improve the locomotion and the reaching of the target.

Second, the visual cues are useful for object location in the mobility space. Indeed, they are useful for obstacles avoidance and for gait adaptation [30], and for verifications between planned and effectively executed path (via (conscious/unconscious) matching of expected and effectively perceived cues).

Third, the distance to an object is estimated at the beginning of the trip (in its starting point). Consequently, there is no continuous update of this distance during the displacement. The distance estimation is independent of the 3-D motion perception and of the optic flow [31].

Fourth, precision of distance and angle estimation may be increased when a cue is seen by the navigator [32].

The reliability of visual cues, i.e., the coherence of the information attached to them in the global traveled space, is a key point for spatial mobility. Jacobs [33] claims that reliable cues play a dynamic role in the visual and spatial learning.

The importance of visual information has been shown through several experiences. Breuneval [34] noticed that a drift from the planned straightforward path occurs when congenitally blind subjects move in large open spaces (such as the university hall). Cornell and Bourassa [35] observed that the blindfolded subjects underestimate or overestimate angles while traveling on, respectively, more curved or less curved paths. The tactile version of “homing” experience [36] confirms these latter results. During a turnaround of an obstacle more than 60% of blindfolded participants did more or less one turn, but they were convinced that they did one whole single turn (360°).

This confirms that nonvisual information alone is insufficient for accurately encoding the angular value of the travels [35, 37].

2.1.3 Putative Explanations of the Dominant Role of Vision During the Mobility

Several studies confirm the dominant role of vision in space perception and understanding during navigation [38, 39]. Other senses, such as vestibule or kinesthetic data, contribute only to a rough estimation of external space parameters (distances, angles, directions, etc.) [40, 41].

Several plausible explanations of the dominant role of vision exist.

Berthoz [42] links vision dominance to the (huge) size of cerebral network involved in visual data acquisition and processing (from low-cognitive (sub-cortical) level to high cognitive (cortical) level with interactions with attentional and conscious processes). Waller and Greenauer [43] explain the visual dominance over proprioceptive and vestibular data by source of the processed information, respectively, external (external-world-dependent data) and internal (ego-dependent data). As for us, the vision dominance seems to be finally related to the size (volume) of the data which must be processed.

Ohmi [20] claims that the visual data is necessary and sufficient for ego-motion (speed and acceleration) perception, while Li et al. [44] showed that these data are fundamental for controlling heading direction and locomotion.

Finally, the vision seems to structure proprioceptive and vestibular data, especially the ego-distance estimation [45].

When reproducing, during the mobility in illumination conditions, a passive rotation previously performed in darkness, the oculomotor activities indicate how the vision system involves the way vestibular data are memorized with respect to different patterns of space arrangements.

Moreover, the vestibular activity is linked to different navigational strategies. According to Siegler et al. [46] experience, participants rotated in complete darkness with large shifts in beating fields used an allocentric navigation strategy when they perform a rotation task, while other participants used an egocentric navigation strategy for the same task.

More recently Israel et al. [47], showed experimentally in the "without vision" condition that for short distances (2–4 m) the distance reproduction is better than for the longest ones (usually undershot) and the error is smaller without vision at short distances; therefore, vision is not necessary for linear short distance navigation.

2.2 Proprioception

The proprioception is the information acquired by the body of relative positions of its subparts while moving [42]. This concept well known to musicians, corresponds to the construction of a body internal presentation which encodes all muscular, articular, and tendon sensors data in order to calculate the precise movements of articulations with respect one to another, their velocity and the strength.

The proprioception is of fundamental importance to keep one's orientation in space, to allow one to walk in complete darkness (and keeping his/her balance), to allow a violinist to play a concert with closed eyes. The proprioception reinforces the perception and learning of visual inputs while moving and allows the update of the body internal presentation necessary for successful locomotion [48, 49].

According to [50], the appropriate integration of the proprioceptive stimuli improves the execution of spatial tasks such as path integration. In the case of failure of the proprioceptive system (for some pathological or emotional reasons), subjects cannot move normally their body in the space and must relearn the convenient movements by visually controlling the body movements [51].

In healthy subjects, the proprioceptive information is insufficient for a precise estimation of the ego-motion during the mobility. This limitation may be due to the interaction between vision and proprioception [52]. However, in some groups with very well trained proprioception (such as musicians, dancers, circus people, skiers), the locomotion seems to rely mainly on proprioceptive data without any vision coordination [13].

The above findings tend to confirm a certain degree of plasticity and of adaptive flexibility of the human locomotion system [53].

2.3 Vestibular Data

The vestibular system seems to be the principle control system of balance. It is localized in the vestibule (inner ear) and is composed of two anatomical structures:

- the three semi-structural canals (stimulated during head angular motion as they are sensitive to rotations and to the perception of angular displacements, [54, 55]), and
- the otoliths (stimulated during head linear translation).

Therefore, the vestibular system provides data on perception of velocity (linear and angular) during the locomotion and assists the orientation in mobility space.

Moreover, the vestibular system keeps a stable external image on retina during the locomotion. Indeed, the vestibule-ocular reflex (VOR), neural links between vision and the vestibular system, is in charge of providing a clear vision during the head and body movements. During locomotion, the head movements must be rapidly compensated in order to generate the clear view of the traveled space (otherwise, the image of this space will be a sequence of individual separated images). The visual coherence of a 3-D space is achieved with signals projected from the semi-circular canals to eye muscles via three neurons (three-neuron arc). Indeed, this arc transmits signal of VOR mechanism, an automatic eye movement compensation mechanism generated from head movements.

The VOR is a mechanism independent of any other sensory systems. When during the travel, the mobility target is modified, the locomotion mechanism plasticity can involve the VOR reorganization only even in the absence of vision [56].

VOR contributes to the emergence of the percept of position and of ego-motion in the space [57]. However, the VOR alone is insufficient to maintain the stable image on retina during the motion [58]. Indeed, the vestibular system usually acts in conjunction with other sensory mechanisms (combination of heterogeneous data). The combination of

(a) vestibular and vision data contributes to the better perception of the body motion and the execution of high level cognitive tasks sub tending the mobility [59];
(b) vestibular and proprioceptive data contributes to the static representation of traveled path, in both real and virtual navigation [60];
(c) vestibular and podokinetic data contributes to accurate perception of body orientation in space [61];
(d) vestibular and somesthetic data contributes to the estimation of the traveled distance and some dynamic characteristics of the motion such as speed and duration.

All these known aforementioned functions are fundamental for human mobility reproduction [62] and prove the role of locomotion in human evolution.

2.4 Multisensory Data Integration and Its Brain Support

Multisensory integration is the process which allows the coherent perception of an experience (e.g., the mobility) thanks to the combined information originated from different sensory and human body sources. For example, optic flow and proprioceptive data are integrated during gait and locomotion [63]; proprioceptive, vestibular, and (peripheral) vision data are combined in body tilt perception [64]; the constant velocity ego-motion percept emerges from a combination of vestibular and vision data [65].

Sensory integration relies on specific brain networks, however, the precise integration process is unknown and prior knowledge is often required for interpreting the sensory signals [66].

The sensory data (visual and auditory) start to be processed in structures such as mid-brain and brainstem.

Superior colliculus (a part of the mid-brain) contains multisensory neurons and are involved in the (saccadic) eye movements, multisensory and visuo–motor integration, and eye-head coordination [67].

The superior temporal gyrus, linked to the superior colliculus, participates in integration of visual and auditory stimuli.

The medial parieto-occipital cortex is activated by visual stimuli, while the parieto-insular vestibular cortex is not activated. This implies that a cortical visual-vestibular inhibitory mechanism exists and it is activated during the ego-motion. The existence of such mechanism may be related to the minimization of the potential multisensory (visuo-vestibular) incoherencies in cases such an unexpected head acceleration during the locomotion; in such conditions, only reliable and dominant sensory information could be used for ego-motion perception [65].

More recently, a "perceptive binding" mechanism has been discovered [68, 69]. This, not yet well known temporal-perceptive, process seems to be based on parallel but independent processing of different sensory modalities in different brain areas, which results are later combined using temporal information (temporal synchronization; [70]).

The sensory integration may lead to sensory conflicts which may occur when the mismatch occurs between acquired and the expected sensory data during a specific spatial tasks [71]. Several theoretical frameworks and computational models have been proposed for such situations. Zacharias and Young [72] and Borah et al. [73] model the interaction of visual and vestibular data during the motion. In 1992 Glasauer [74] proposed his model of the interaction of visual and vestibular data during the motion delivering the similar predictions to Borah's model. Merfeld and Zupan [75] extended Borah's model to interactions of sensory and VOR information during spatial orientation tasks.

The information generated during mobility is usually redundant [76], as data from different modalities may be combined differently through different brain networks. For example, in the case of mobility (walking), the brain receives information from vision, vestibular, and proprioceptive systems. The vision system, through optic flow and visual cues, contributes, between other functions, to the detection of objects, to distance estimation, to path planning, to effective path recognition, etc.; the vestibular system contributes, between other functions, to the estimation of the velocity modifications (acceleration) and rotations' angles; the proprioceptive signals give feedback of posture and the course of displacement.

Recent works have shown [37], that one sensory modality alone does not provide sufficient data for emergence of a precise concept from perceived stimulations, as their values can be noisy or insufficient [36]. Therefore, as some authors suggest [77, 78], the availability of various sensor stimuli may not improve the emergence of a specific concept but may define the area to which it belongs.

3 Movement Perception and Spatial Navigation

The sensory information related to spatial navigation is processed by dynamic mechanisms called cognitive strategies. The three main human mobility strategies are: path integration (Sect. 3.1), landmark-based strategy (Sect. 3.2), and geometry-based strategy (Sect. 3.3) [79, 80].

3.1 Path Integration

Path integration (PI) is a continuous cognitive process which updates the current position (location) of the navigator with respect to a given reference point, usually path starting point. This update uses signals generated by the locomotor system from performed translations and rotations [2, 81, 82].

Two subclasses of PI can be considered: simple and complex.

In the cognitively simple spatial tasks, the human navigator exhibits elementary behavior through paradigms such as distance estimation, following a linear segment or triangle (homing) task.

The classic triangle homing task involves naïve blindfolded participants. They learn to navigate and to estimate the distance between two line segments: AB and BC; next they navigate from A to C directly (not via B). The final goal of this task is the distance estimation after the locomotion based on solely proprioceptive and vestibular signals.

Proprioceptive cues, i.e., kinaesthetic data generated by the motor system, are fundamental for traveled distance estimation. If the pace rhythm varies from usual, the traveler overestimates (in the case of higher rhythm) or underestimates (in the case of lower rhythm) the distance unless some vision information is available [83].

Vestibular data are linked directly to the performed rotations and accelerations. In order to return to his/her starting point following a predefined path, the traveler needs a global orientation toward the starting point. Physical rotations of the body modify the status of vestibular data; they allow the orientation estimation.

Although proprioceptive and vestibular data are necessary for PI, the vision data, even briefly presented to the navigator during the mobility, significantly improve the PI and the homing is successfully achieved [36, 84].

For a simple travel path in the homing task, with few rotations and few linear segments, the PI may produce the spatial representation of the traveled path [85]. For more complex travel patterns, the PI performance reduces drastically, and systematic errors in heading direction estimations and in distance estimations occur. Wang and Spelke [79] suggest that if the presence of a cognitive presentation of the traveled path would occur during the PI, errors in distance and orientation estimation would be independent of the complexity of the traveled path and no systematic relation between them would be noticed. Fukita et al. [85] and Foo et al. [86] argue that the PI cannot lead to a precise cognitive presentation of the traveled path, without other navigational cues such as landmarks. Experiments by Rieke et al. [87] suggest that the visual PI, without any vestibular or kinesthetic cues, can be sufficient for elementary navigation tasks such as rotations, translations, and triangle completion.

However, the precise contribution of the PI to spatial cognition is still an open question.

3.2 Landmark-Based Mobility Strategy

A landmark is an object which offers unique specific perceptual characteristics which make it distinctive from other objects located in its vicinity. Landmarks are used during way finding and spatial learning [88, 89]. These perceptual characteristics are of different nature; shape, color, texture, form, etc. They are mainly vision characteristics while smell, temperature, or environmental noise are characteristics which may be perceived with other senses.

Landmarks may be global or local for a considered navigable space. A global landmark can be perceived from any point while a local landmark is perceived only locally (in a short distance). Both, global and local landmarks may provide directional and positional information, however, a global landmark will provide such data regardless the position of the navigator in this space, while the local landmark may provide them in a short distance to the landmark. Some authors [86, 88, 90] suggest that the navigator learns landmarks in decision points and navigates using a graph of memorized landmarks. Visually impaired people learn landmarks also in points which allow them to confirm the progress of their travel [34, 91, 92]. Familiar landmarks play a definite role in remembering the decision points during mobility [93].

The use of either global or local landmarks varies with personal preferences [94]. The local landmarks are more important in active (real) than in virtual navigation [86], while the global landmarks contribute to the distance estimation in large-scale environments [95].

Landmark-based navigation strategy is an episodic process of spatial learning [2] and is based on “episodes” bound to the considered landmarks in such a way that all episodes lead to the reconstruction of the trajectory of the path taken.

The use of landmarks varies with age. Children (of 30 months old) use landmarks in order to find a hidden object in a room [96]. Children and pre-adolescents exploit (different) landmarks for distance estimation during navigation [97]. Adults use landmarks in conjunction with path integration (PI) strategy as landmarks increase the accuracy of navigation [86].

Landmark navigation strategy contributes to the updates of space knowledge and to the recognition of familiar view-dependent scenes [98].

Landmark-based spatial learning activates specific brain networks such as parahippocampus and hippocampus cortex [99–102].

3.3 Geometry-Based Navigation Strategy

Geometry-based navigation relies essentially on the knowledge of the geometry (a global configuration) of the navigable space, i.e., on objects of the navigable space and their relative spatial positions (metric–geometric relationships).

Usually, the geometry data is a visual information, but it can be also tactile, kinesthetic, and auditory information.

During navigation this information is updated with an episodic cognitive process.

The effectively used strategy when performing various tasks is a function of at least two parameters: size of the space and form (shape) of the space, and it varies with age.

During the reorientation tasks in a small room (4 × 6 ft) (with a goal reaching, i.e., finding a hidden toy), children (until the age of 3 years old) use mainly the geometry properties of a room [79, 103, 104]; after disorientation in a familiar room children rely on symmetrical geometrical properties of the room. In larger rooms (8 × 12 ft) with furniture, children rely also on landmarks and reorient themselves to find the hidden toy [96, 104]. In adults, the orientation tasks are mainly based of landmarks of a (small or large) space.

The space form is another important parameter for navigation strategy.

Experimental studies with children confirm that rectangular-shaped spaces provide a limited geometric data as there is no distinctive information (as all angles are of 90°); other shapes (isosceles triangles, kite-like shapes, trapeziums, rhombus) are more informative [105–107]. Furthermore, the same studies evidence that landmark and geometric information in the enclosed spaces are unique and undivided knowledge globally and simultaneously encoded by children.

Experimental studies with adults show that for large-scale environments the geometry influences the estimation and reproduction of the traveled distance. Ruddle and Peruch [95] report that when the perimeter of the environment was oblique, the navigator follows a longer segment than when the perimeter had an orthogonal shape. Buckley et al. [108] report that in virtual navigation, humans encode a global representation of the overall shape of the environments in, or around, they navigate.

Based on animal studies, Gallistel [2] proposed the "long axis" theory of navigation. This theory hypotheses that the space geometric information is encoded using main axis of the navigable space (and not global geometric configuration) as the entire space is structured around the main axes. Consequently, the environment's detailed structure has little impact on navigation as the navigator mainly focuses on the axes and not on the perimeter of the environment.

Valiquette et al. [109] experimental works support Gallistel's theory. An array of objects placed inside orthogonal spaces were memorized and then recalled by adults; the collected results show that the objects were learned by respecting the axes of the orthogonal layout and were recalled as if positioned in rows and columns with respect to these axes.

It should be noted that the GPS-based way finding implements Gallistel's theory. Indeed, the "long axis" theory requires the small cognitive load and it is the simplest for explaining, memorizing, and implementing during the navigation [36].

3.4 Reference Frames

Reference frames are means to find data in the space to which they are attached.

Cognitive reference frames allow to understand which data are encoded by brain mechanisms.

Two main reference frames are considered: the egocentric and allocentric. Egocentric (or first person) frame encodes spatial data (e.g., locations) with respect of the observer's body perspective and position. Allocentric (or third person) frame encodes spatial data using an external—to the observer- point which is independent from the observer.

The human brain uses two reference frames for spatial data encoding.

The allocentric reference frame allows to encode relative positions of several fixed objects simultaneously, without interfering with the observer's position and view point. It is possible to speak about "map-like" (or mapping) encoding obtained with "survey learning" process. This process seems to be implemented during mental (virtual) navigation in a space, if the user mentally visualizes the map and moves in it [110, 111].

The egocentric reference frame seems to be used in the process where spatial learning is implemented during the route learning via active navigation of the observer in the space.

As both reference frames are important for mobility assistance, both should be supported by the technologies when necessary.

4 Neural Evidences of Spatial Cognition

This section proposes a state of art on the neural supports for spatial cognition and spatial learning (cf. [112–114] for detailed overview of the question). This section may lead to new ideas on the design of control systems for intelligent mobility assistances for visually impaired people, for humanoid robotic systems, and more general, for autonomous mobile intelligent system.

4.1 Hippocampus and Spatial Information

Scoville and Milner's studies [115] on spatial memory established the contributions of the hippocampus and some parts of parietal cortex; epileptic subjects with excision in hippocampus showed sever spatial amnesia.

Berthoz [42] recalls several studies which deep Milner's results to parahippocampal area and includes the processing of multisensory spatial information (vision, smell, auditory).

Spatial navigation capability and hippocampus activities are strongly correlated [110, 116, 117]. The hippocampus is activated on the view of places during the navigation [100, 116], on encoding [118] and on retrieving of topographic data [119, 120]. The hippocampus role in allocentric topographic data encoding is unclear [100, 119 versus. 103, 121].

Several studies confirm the role of hippocampus in route planning toward a specific target inside large-scale familiar spaces [122].

Other studies suggest that the hippocampus and other structures of the medial-temporal lobe are fundamental for spatial information encoding in the long-term memory, but they do not participate in recalling of spatial data encoded in the remote past [123].

The hippocampus plays an important role in a target-oriented navigation as it retrieves information from a cognitive map stored as allocentric representation of the known space in order to perform path planning tasks [122].

The activation of both hemispheres of hippocampus differs. The patients with lesions in the right hemisphere are unable to perform spatial allocentric tasks [124] such as survey learning [111], while those with lesions in left hemisphere perform similarly to the healthy subjects.

4.2 Parahippocampus and Spatial Encoding

The activation of parahippocampus occurs during the egocentric spatial tasks such as navigation [116, 125], especially during landmark recognition and spatial views [99, 100].

Parahippocampus activation may be bilateral or unilateral.

Bilateral activation was observed when encoding data of large-scale environments or buildings. Unilateral activation, limited to the right hemisphere was observed during this information retrieval from a long-term memory [126] or during the recalls of familiar landmarks located in a specific spatial context [99].

Burgess studies showed the activation of the right parahippocampus and right posterior parietal and posteriodorsal medial parietal cortex during the retrieving of spatial context [127].

Deficit of the allocentric presentation and of visuospatial encoding and recalling was found with spatial disorientation tasks performed by subjects with lesion on the right medio-temporo-occipital lobe (parahippocampal sulcus included) [128].

4.3 Hippocampus, Parahippocampus, and Spatial Memory

Hippocampus and parahippocampus work in synergy when the brain spatial presentation is generated [129]. Dynamic role of both organs is claimed by Aguirre et al. [121] during topographic encoding and recalling.

Bilateral activation of hippocampus (when encoding allocentric data) and of parahippocampal sulcus (when encoding the egocentric spatial data) was confirmed by several studies [127, 128, 130].

When retrieving encoded spatial information, the activation limited to right hemisphere was observed by some authors [127, 128, 130], while others observed it in the left hemisphere [102, 120].

Lambrey et al. [131] provide some elements for these contradictory results on hippocampal activation. They designed an experiment for a navigation task in a virtual reality maze and tested it with three groups of subjects: healthy (control), right medial-temporal lobe (RMTL) patients, and left medial-temporal lobe (LMTL) patients. The maze contained distinct objects (landmarks) in every road intersection; the path to follow was designed by green walls, while red walls indicated wrong directions. The navigation test in the maze has been performed five times, and each navigation ended with a drawing of the traveled path (with closed eyes). Participants named landmarks in the order they thought that they had appeared during their navigation. The collected results show that both (left and right) median-temporal lobes are involved in spatial memory but with different contributions: right median-temporal lobe is implied in survey (allocentric) spatial encoding, while the left median-temporal lobe is mainly implied in egocentric tasks (associative learning, route memory). This laterization could explain the contradictory results of the previous works on hippocampal activation.

The above results show clearly that the precise role of hippocampus and of parahippocampus is still an open question.

4.4 Parietal Cortex and Spatial Processing

Parietal cortex plays an important role in egocentric spatial processing [132].

During route learning (i.e., egocentric spatial encoding) an important activity in posterior superior and inferior parietal areas (the precuneus included) was evidenced [121, 133, 134]. Wolbers et al. [133] suggested the involvement of parietal cortex in temporal processing during learning tasks.

Works by others [99, 111, 121] show that parietal cortex and precuneus is involved in allocentric spatial tasks such as way finding and changing of the view point (tasks which are based on cognitive maps).

Studies with hemi-neglect subjects showed the importance of parietal structures in attention processes. In most of the cases these subjects have a lesion in the right parietal lobe, and present attentional deficit for the visual stimuli in the opposite (left) visual field.

Therefore, it is possible to say that parietal cortex plays an important role in spatial learning and recalling for either egocentric or allocentric reference frames of space presentations. It seems also that the parietal cortex is a part of a larger network involved in the spatial encoding and learning processes.

4.5 Frontal Cortex and Spatial Processing

The activation of the frontal cortex was evidenced during both encoding and learning processes, independently of the used reference frame.

Superior and medial frontal gyri are activated during the encoding of routes and of spatial environments [133], during the recalling in way finding tasks and in environment recalling [99, 111].

Prefrontal cortex is activated when performing some process-specific functions such encoding, recognition and recalling [135, 136], and this is independent of the context-specific functions (spatial vs. non spatial memory).

This specific role of the prefrontal cortex was evidenced by neuroimagery studies (PET, fMRI) during which the activation of the dorsolateral prefrontal cortex was registered during the way finding tasks [120].

According to the above results it seems that the frontal cortex is a coordinator of memory and way finding processes.

4.6 Wide Neural Network and Spatial Processing

The aforementioned brain structure works in cooperation and redundancy with other structures in the implementation of high level cognitive spatial tasks [137] via wide brain networks.

Committeri et al. [130] showed that:

- retrosplenial and ventromedial occipito-temporal cortex, and ventrolateral occipito-temporal cortex are involved in allocentric spatial tasks;
- dorsal stream (connected to frontal regions) are mainly involved in egocentric spatial presentation (first person);
- distinct neural substrates are activated for ego and allocentric tasks.

In complex environments the synergistic activity of different cortical areas was stated. The egocentric tasks activate parietal and frontal premotor areas, while allocentric tasks activate the parietal-frontal, ventromedial occipito-temporal and retrosplenial regions.

In topographical and spatial orientation tasks (such as activation of cognitive maps) retrosplenial and anterior hippocampal cortex work in parallel and in synergy [138, 139]. Especially, the retrosplenial cortex plays a significant role in the coordination of the spatial information retrieved during the mobility by integrating new information, updating the already existing spatial presentation of the cognitive map related to a specific environment. This allows the update of the ongoing route planning [122].

The above-related studies indicate that several distinct brain areas are involved in the spatial behavior processing; however, the precise role of each area is still unclear.

Possible explanations of such situation may be the complexity of the cognitive processes underlying the mobility and the inadequate experimental instruments and procedures, huge number of parameters which underpin the simplest mobility function and, finally, large interpersonal variability of cognitive behavior during the mobility tasks.

5 Spatial Cognition of Animals

Scientific knowledge of animal spatial navigation and spatial encoding allowed progresses on human spatial cognition thanks to the phylogenetic theory which assumes that brain structures evolved according the species' evolution in an ascending way, from low-level species to above species until humans.

This section recalls the main findings on cognitive mobility strategies in animals which are similar to human main strategies: path integration, geometry-based and landmark-based strategies.

5.1 Path Integration and Homing

PI is a navigational strategy common in all animal species, from insects to mammals, activated mainly outdoor in large environments [140].

PI in rodents (including hamsters, rats, and mice) is generated by internal signals produced during the locomotion such as proprioceptive and vestibular cues [141].

Self-motion cues allow constant estimation of the animal's position with respect to its nest as the reference (initial) point. The PI alone during foraging does not allow an accurate homing process. In animals like ants and hamster, PI vector undershoots the traveled distance; the longer the journey, the greater the underestimation is. In order to compensate this distance underestimation and return home effectively, animals rely on the view of vision cues (landmarks). These landmarks confirm the PI vector's estimation and correct it, if necessary [139, 141]. Collet and Graham [142] distinguish two types of vision cues based on whether vision cues are interaction with it or not.

Insects, ants and bees can use either landmarks-based navigation in familiar environments or PI (vector navigation) in unfamiliar environments. The precise role of landmarks (visual, olfactory, etc.) is still an open question [142]: does the view of landmarks reset the estimate of the PI vector? Does the view of a landmark is used for confirmation of the vector estimation toward the nest? In their inbound travel ants use a simple approximation of the PI vector calculation; this vector is subject to small systematic errors; therefore, this vector does not allow to reach the nest itself but only the nest periphery [140]. For this purpose, ants rely on familiar landmarks positioned around and in proximity to the nest [143]. More recent studies [144, 145] claim, that "for [ants (rats)] robust scene recognition what matters is the spatial arrangement of the objects across the scene, and not the identification of specific individual objects" [145].

Bees need to rely on visual or other cues (olfactory) even in order to perform PI; it seems that PI in bees is considered as a complex behavior [146, 147].

Studies in rodents contradict these results. The role of landmarks in rodents' navigation is unclear. Some experiments shows that PI vector can be redirected when viewing familiar cues [148–150], therefore visual cues provide spatial information, computed along PI, and useful for the update of homing vector. Studies by others [150] show that a visual cue resets the PI and allows direct return to the nest based of the visual information. Recent works suggest that landmarks coordinate the activation and encoding mechanisms like PI [151].

PI is a common behavior in the animal kingdom, as mobility is a fundamental activity for their survival (e.g., food collection, safe homing, etc.). However, the exact mechanism of PI and the way how external (visual, olfactory, etc.) data impact the PI is still an open question.

5.2 Geometric Based Navigation Strategy

In indoor space, where vision landmarks are available for reorientation, the non-human species rely mainly on geometric properties of the navigable space for navigation subtasks (orientation, recognition [152]).

Two problems have been investigated so far: (1) which geometric properties are exploited during the spatial navigation (and their encoding); (2) relationship between these geometric properties and other spatial properties such as landmarks.

The 'disorientation task' is a classic paradigm for search of the geometric properties. Several studies show that many animal species rely essentially on geometric cues (e.g., the global configuration of the navigable space) in order to reorient themselves inside limited environments. Rodents [148, 153], pigeons, rhesus monkeys [154] reorient themselves using the global shape of the near closed environments, regardless of the type of the shape (rectangular, square, etc.) and its size [155]. Humans use not only cue salience but also cognitive complexity of the environment in which human is supposed to reorient to [156].

All the above studies suggest that geometric properties of the navigated environment are modular and may be supported by a "brain geometric module" activated during spatial tasks [152]. Moreover, animals encode geometric data independently of the presence (or absence) of other environmental cues.

This means that independently of other sensory cues experiences by animal during the navigation, the geometric learning of the environment is a compulsory process of its spatial behavior [152, 157, 158].

Principal axes of the navigable environment seem to be mainly geometric data encoded [144, 145, 152, 159]. These results support Gallistel's 'long axis' theory for mammals' spatial navigation [2]. Consequently, the learning process during animal navigation seems to be concentrating on spatial data near by the axes (cf. §3.3. for the human learning process [160]).

5.3 Landmark-Based Navigation Strategy

Generally, animals rely on visual landmarks in spatial tasks. Honeybees use extensively landmarks when approaching to the target [161, 162], when they need to redirect PI vector. Ants associate the view of landmarks nearby their nest with local PIs; during inward journey these vectors are activated only in the presence of the known landmarks. The encoding mechanisms can be activated independently but in parallel to the PI mechanism [163].

Vision landmarks seem to dominate other types of information. Adult rats, contrary to young rats, privilege vision cues over olfactory cues [164]. Mountain chickadees seem to ignore the geometric features of the environment when other salient visual landmarks are available [165].

There is no scientifically proven explanation of such dominance. Experiences with rhesus monkeys [154] indicate that they tend to rely on voluminous landmarks to distinguish symmetrical corners inside test-rooms and tend to ignore small-sized landmarks. This suggests that local and small-scale environments do not suffice to dominate or overshadow the geometric encoding.

Landmark encoding and geometric encoding of spatial knowledge in rats are probably due to distinct mechanisms, possibly independent, but usually activated in parallel. In some circumstances the landmark-based encoding may overshadow (without cancelling) the encoding of the geometric features [166]. However, no competition is observed between landmark and geometry encoding in the case when the geometry-based learning uses global shape and not local geometric properties [167]. In goal searching tasks, if geometry and vision cues are coherent neither competition nor overshadowing was stated.

When two stimuli are not coherent, vision stimulus dominates spatial encoding [168]. Finally, McGregor et al. [169] claim that spatial learning based on local landmarks and global landmarks are two mechanisms which may work independently and in parallel, one complementing the other.

6 Toward a Structure of Spatial Knowledge

Different concepts have been proposed to model the spatial knowledge. In this section we present the most popular model: cognitive map (Sect. 6.1); its physiological evidences (Sect. 6.2), and two models, sequential and parallel, for spatial knowledge acquisition (Sects. 6.3 and 6.4, respectively).

6.1 Concept of the Cognitive Map

Gallistel [2] defines a brain representation as a functional isomorphism in the mathematical sense of the term, that is, a bijective correspondence between two systems. Thus, in a representation of the space it is possible to find the information giving a coherence to the environment in which one evolves.

The term “cognitive map” has been introduced by Tolman [170] as a brain presentation of navigated spatial location, while the cognitive mapping designs a process of spatial knowledge acquisition and this knowledge coherent structuring in a robust presentation which may control the motor system during the navigation.

The content of the cognitive map is established from all sensory and kinesthetic data which occur during the mobility. Indeed, the mapping is activated by processing of sensory data, including perceptual properties of the physical space, subject internal state including the memories produced by previous experiences with space interactions (physical properties of the environment, socioeconomic data, expected data on the current environment, etc.) [171, 172]. The space presentation includes both, allocentric, and egocentric forms of spatial knowledge [172].

Topological and metric data of environment experiences are fundamental elements of cognitive maps [2]. That is why two types of internal presentations of space are sometimes considered: topological maps and cognitive maps.

According to [173], the spatial organization of sensory data is reflected in the spatial configuration of some of the data processed in the brain. Recent research has made possible to locate certain brain structures in which these topological maps are observable. For example, in the parietal cortex different regions representing the stimuli, according to retinotopic or somesthetic organizations [174].

However, this type of spatial organization of space only allows to reference the objects in the space linked to the sensor. To construct allocentric representations, it is necessary to create representations in a more global reference frame.

According to Denis [175], cognitive maps allow:

- to know where we are at any time in our environment,
- to identify the position of objects without direct perception,
- to choose the path to take,
- to communicate to others our spatial knowledge.

Some authors [176, 177] are interested in the mathematical properties, and mainly in the metric of these spatial representations in order to propose models reflecting the imperfections of our perception.

Cognitive maps are not identically produced in all humans, as their content is related to personal experience. Landmarks contribute significantly in the emergence of coherent cognitive maps after physical navigation, and they probably have a role of “anchor points” which structure the whole spatial information during cognitive mapping [178].

6.2 Physiological Evidences for Cognitive Mapping

Many studies attempt to understand how representations of space are formed at the level of our brain. Experiments initiated by O’Keefe and Dostrovsky [179, 180] in rats revealed the existence of specialized cells for this task in the hippocampus. Indeed, “place cells” discharge selectively, i.e., when the rat is in a well-determined position of space. If the rat changes its place or if its space changes the content, the mapping process resets all place cells and activates new place cells in relation to the new space. The activity of these cells is directed by the information coming from the different sensory modalities [181]. Mathematical models of the functioning of these place cells have been proposed [182].

The place cells do not reflect the structure of space itself: they inform about our position in the latter.

Another type of neural structures, head direction cells, provides a sense of direction in some species (rodents and rats [183]). The cells also discharges selectively and independently, the animal’s position in the environment, when the animal’s head is oriented toward a specific direction. Place cells are localized in anterior dorsal thalamic nucleus (in Papez circuit), and they continuously process information of heading direction during locomotion [184].

Studies on human cognitive mapping show the involvement of hippocampus which seems to process metric information and seems to contribute to the generation of allocentric cognitive maps [185]. Recent neuroimagery studies showed that acquisition of cognitive maps in humans relies on hippocampal function complemented by retrosplenial activity [138].

6.3 Hierarchical Models of Spatial Knowledge Acquisition

The first models of the spatial knowledge acquisition process suggested that it is acquired sequentially and by combination of different sources of spatial information [176, 186].

Shemyakin [187] claims that "the acquisition of spatial knowledge progresses consecutively from landmark recognition to path definition and the understanding of general relational characteristics of areas". This means that from more perceived data you can generate more precise cognitive maps.

Hart and Moore [188] and Siegel and White [189] proposed multilevel models of spatial knowledge acquisition. At the first level the landmark knowledge is acquired; at the second level, route knowledge occurs between landmarks. Both elements are organized into clusters with metric relationships at third level. At the final level clusters are linked in schematic and systematic structures and they form the survey knowledge.

These hierarchical models correspond to the way in which we organize the information in order to compute it on our computer system, and their effective existence in the brain is still an open question.

6.4 Models of Parallel Acquisition of Spatial Knowledge

These models hypotheses that different sensory data interact between them on a quantitative (and not qualitative) basis [190]. Montello model [191] defines five principles allowing to acquire the spatial knowledge; they are: (1) parallel acquisition of all different types of spatial knowledge; (2) parallel increase of the volume of acquired sensory data; (3) integration of elementary places into more complex hierarchically organized knowledge; (4) inter-individual differences may play an important role in the spatial knowledge integration; (5) linguistics systems contribute to structure the already existing spatial knowledge.

Montello's model was tuned by others.

Jackobs and Schenk [192] proposed the "parallel map theory" (PTM) based on anatomical, functional and behavioral data collected from animals (reptiles, rodents, primates). Two parallel cognitive maps work: the "bearing map" and the "sketch map."

The bearing map encompasses directional and idiothetic cues, and produces coarse-grained presentation of space useful for long-distance navigation.

The sketch map encodes all position cues (landmarks) respecting topographic relationship between them. This is a fine-grained map of a local space and suitable for local navigation only.

Finally, a third-integrated cognitive map is built from the two above maps; it allows short and long path navigations.

The PTM model has its own update process which allows the spatial information recovery in the case of encoded data missing.

Roche et al. “neurocognitive map” [172] combines PTM based on animals studies with studies on humans. The model proposes a presentation of human brain structures that correspond to each cognitive aspect of the model. The acquired spatial data belong to one of three classes: functional presentation, egocentric presentation, and allocentric presentation.

The functional presentation corresponds to information acquired from path integration during locomotion.

Egocentric representation encodes information of places visited during navigation, and is linked with route-spatial knowledge.

Allocentric representation is supplied by an external sources of spatial knowledge such as a survey map.

The combination of these three mental constructions produces a neurocognitive map (which is supposed to exist in cortical and sub-cortical areas).

The PI (or functional presentation) process is subserved by the vestibular and proprioceptive systems, the parietal somatosensory regions, and the dorsal visual system. Egocentric representation draws from the fusiform gyrus, inferior temporal gyri, and superior parietal cortex. Allocentric representation involves the parahippocampal gyrus and/or the lingual gyrus. This brain support of the neurocognitive map needs more experimental studies.

The Mou et al. model [193, 194] is based on human behavioral data. This model claims that human behavior is induced by the two subsystems, the egocentric, and the environmental. The egocentric subsystem encodes the data received during the locomotion and includes relationships “self-to-spatial” (e.g., obstacle avoidance while walking); this information gets activated only during the navigation. The environmental subsystem encodes the static and enduring elements of the navigated environments and represents them in “intrinsic reference frame”. During spatial navigation, the spatial encoding occurs by updating the intrinsic reference frame.

Recent work by Finaly et al. [195] provides support to this model.

7 Conclusion

The proposed overview shows that animals and humans spatial behavior display several similarities. The same navigation strategies (PI, landmarks, and geometric features) are used for the spatial learning and encoding the navigated space.

The contribution of PI in human navigation is demonstrated only in simple spatial tasks such as homing. Future studies of PI’s participation in more complex spatial tasks are necessary. It is expected that these tasks may lead to a deep comprehension of its role in human navigation and spatial cognition.

Ontological, neurocognitive and neuroimaging considerations evidence that landmark-based strategy is a substantial mechanism for spatial cognition, providing accurate encoding of spatial experiences.

Geometry-based encoding plays an active role in spatial cognition. However, its precise role and interaction with other strategies of spatial learning (especially with landmark-based strategy) is unclear.

Many theoretical, cognitive, and computational models try to understand the cognitive and brain mechanisms involved in cognitive mapping. Some of these models are based on biological studies in order to be biologically plausible and reliable.

As far as visually impaired people (VIP) mobility is concerned, the main question is how to adapt these models and the existing navigation strategies and allow VIPs to understand and explore alone the space with their own perceptual capabilities.

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Sensory Substitution and the Neural Correlates of Navigation in Blindness

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1 Introduction

Sensory substitution devices (SSDs) are capable of efficiently transmitting visual information in real time via touch or sound. This chapter includes several sections reviewing the different elements associated with the use of SSDs by blind or visually impaired individuals. We also develop the idea that an active reinterpretation of sensory information through mechanisms of training-induced plastic changes enables CB to use SSDs, as if they had access to specific properties of real vision. These properties can include, for example, the shape of an object perceived at a distance, the distance of an object to the observer, or the color of the object. We also review the phenomenological properties of sensory substitution concerning the user's perceptual *sensation* when experiencing nonvisual stimulation. Despite wide use of SSDs for research over many decades, their use is not widespread in the blind population. We suggest guidelines for creating better devices. In addition, we suggest that the activations of task-specific specialized brain areas demonstrate the

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amodality and task specificity of SSD processing. Finally, we examine the literature on the neural correlates of navigation in sighted and blind people. The abilities of blind individuals trained with SSDs in spatial navigation, combined with anatomical and functional changes, illustrate the ability of the brain to rewire itself during perceptual learning and provide novel interpretation of nonvisual sensory information.

2 Sensory Substitution Devices (SSDs)

Sensory substitution is rooted in the idea that it is possible to replace an impaired or lost sense by the novel interpretation of another sense. Paul Bach-y-Rita, the father of sensory substitution as a formulated field, aimed his work at restoring visual functions in blind people [8]. Today, most SSDs attempt to restore visual functions, but not exclusively [16, 181, 219]. In this chapter, we concentrate on SSDs that translate visual information into tactile or auditory information. SSDs usually consist of these three components: a sensor, a processing unit that converts the sensory information using a code or algorithm, and a way to transmit this information to the user.

Visual SSDs differ from one another in terms of their respective approaches for capturing, transforming, and sending information. For example, SSDs differ in terms of the sensors used to capture the visual information. Some use image-based transformations from a camera (Fig. 1a, c) [8, 139, 145], sonic [103] ultrasonic [13, 90], or infrared sensors (Fig. 1D) [51, 131, 194], while others use magnetic sensors instead [101].

SSDs also differ from one another in terms of the algorithm used to translate the *visual* information into another modality. In the case of the tongue display unit (TDU) (Fig. 1a), the image from a camera is translated into electrotactile pulses on a grid of electrodes applied to the tongue (Fig. 1b) (see [171]). In the case of the vOICe (Fig. 1c), visual information is transduced into an auditory soundscape (see [145]). In the case of the EyeCane, the handheld device sends infrared distance

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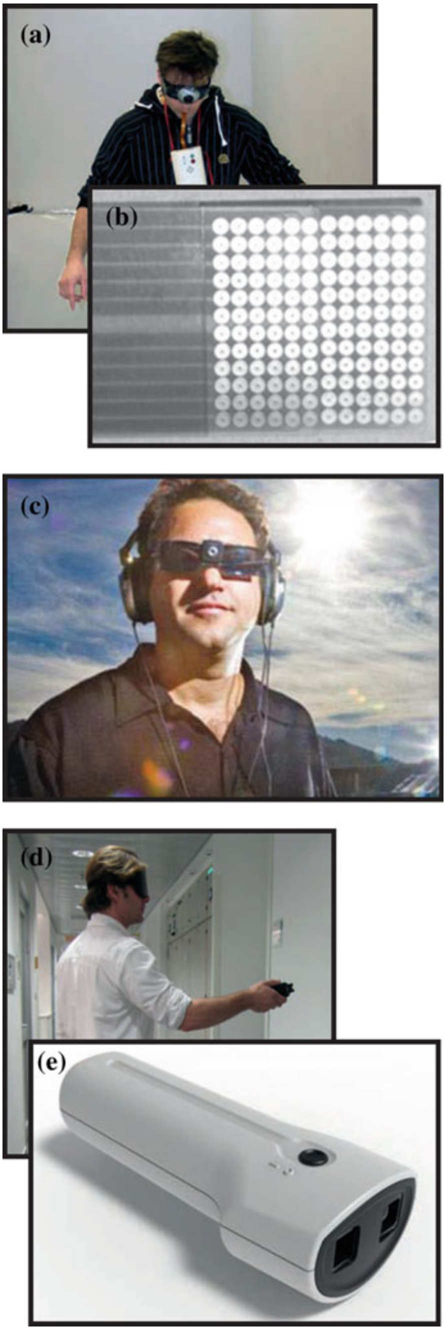

Fig. 1 Sensory substitution devices. Examples of the experimental setup for several different sensory substitution devices. **a** The BrainPort (WICAB) with a camera mounted on a pair of darkened glasses. The *box* on the chest controls the intensity of the electrotactile stimulation. **b** The tongue grid. Applied to the tongue, it delivers a tingling sensation through the electrodes. **c** The EyeMusic experimental setup with headphones and camera. **d** A participant holding the EyeCane that delivers vibrations and sounds to indicate the distance to an object. **e** The sensors of the EyeCane and device

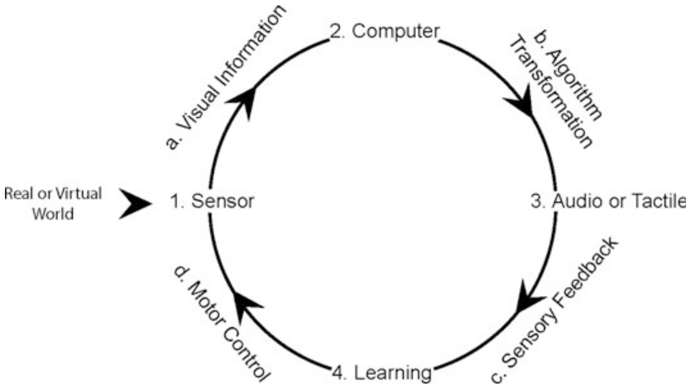

Fig. 2 Sensory substitution motor loop. This loop enables the embodiment of perceptions. *1* The sensor is pointed in a given direction. *2* A computer or microchip analyzes the image and transforms it into tactile or auditory stimulation. *3* The user receives this tactile or auditory stimulation and a percept is generated. The user tests his percept and receives feedback (e.g., by touching the object that was in the camera's path). *4* Learning. The user adjusts his understanding of the code in order to match perceptions with the sensory feedback he receives. *1* The user reinitiates the loop again by moving the device

information in the form of vibrations and sounds (Fig. 1d, e). Despite their differences, for all these SSDs the sensations must be actively *reinterpreted*, from a meaningless tactile or auditory sensation, into a "visual" percept. The resulting perceptual experience after training is in many ways comparable to real vision [8, 111, 171, 220, 221].

Another factor that differentiates between SSDs is the modality used to transfer visual information, usually either tactile or auditory. Thus, the process of learning to use SSDs usually involves the *active* reinterpretation of tactile [8, 131, 166] or auditory information [103, 145] to signify visual information through sensorimotor feedback (Fig. 2).

3 Active Perceptual Learning of SSDs

The process of attributing visual properties to tactile or auditory stimulation can be described as an active sensorimotor feedback loop (Fig. 2), respecting a strict set of contingencies (Sensori-Motor Contingencies: SMCs) [102, 158, 160]. This idea suggests that when using SSDs (or sensory augmentation devices), motor actions linked to sensory stimulations are regulated by SMCs. SMCs are a set of rules or regularities that help relate movement of the user in relation to the object. SMCs must be learned, in effect the user is learning the algorithm that transforms the image into tactile or auditory stimulation.

The SSD learning process can be broken down into several steps (Fig. 2). First, a sensor captures the visual information that is processed via a computer, or smartphone microchip using a code (a specialized algorithm) substituting the visual information into an alternative tactile [8, 224], auditory [145], or both modalities simultaneously [12, 131, 147]. The user gets a perceptual stimulation (auditory or tactile) that represents the image that is captured by the SSD. The user then accomplishes exploratory movements that modify the sensory information. This relation between movement and image helps the user learn the SMC code that governs the image transformation into touch or sound. In order to learn this code, the sensorimotor loop must be rehearsed many times. The user then attempts to interpret the stimulation and casts a hypothesis about his perception. For example, if the sensory stimulation represents a vertical line, moving the camera to the right should result in shifting the stimulus to the right as well. The user then makes the required motor adjustments to test the hypothesis and the loop starts anew. Completion of the sensorimotor loop and exploration through trial and error with SSDs help create an illusion similar to vision. After a training period that can sometimes be very intensive (anywhere from just a few minutes to several weeks of training) and cognitively taxing, touch or sound acquire perceptual properties similar to “vision.”

Once the code has been learned, it requires less attention and the user begins to automatically *perceive* the stimulation as external. This externalization of the stimulation has been described previously as *distal attribution* (for a recent review, [83]). This distal attribution has been linked to a number of tasks usually considered *visual*. Nonvisual stimuli that contain information on shape [5, 6, 171, 198] and motion [170, 198] are interpreted as “visual” by CB. The same is true for obstacles [32] and spatial relations [30, 120]. Bach-y-Rita [10] argued that it is correct to use the term “vision” to describe the sensations experienced by CB and late blind (LB) participants via SSDs because of the “visual” phenomenological percept that they report. The creation of a novel “visual” percept through an already existing modality provides an opportunity to study the impact of SSD training on cortical processing [184].

4 Phenomenological Properties of Sensory Substitution

Participants often report that the sensation provided by the SSD takes on different properties after training. What are then the phenomenological properties of sensory substitution?

4.1 Self-reports

> I took part in a scientific study which enables blind people to be able to visualize objects by stimulation of their tongue. After being introduced to the program, I was seated facing a wall 3 feet in front of me. I was allowed to feel the shape of what turned out to be a very large letter E. After a few minutes of adjusting my head up and down, and from left to right, in carefully contrived movements, I was able to visualize the letter E. This was exhilarating and I could hear my heart beating quite loudly. This was the first time I could visit the world I thought had disappeared when I lost my sight…
>
> A.D., late-blind participant

Anecdotal self-reports from blind people using SSDs indicate that they perceive the information as similar to what they imagine vision to be like, or in the case of LB individuals, to what they remember from their past visual experience. For example, blind participants report many emotions and perceptions, such as the world opening up around them [136], or being able to grasp objects with better precision [120]. They often use terms such as "visualize," or report *seeing* objects or movement during experiments. It is even possible to measure *visual*-acuity via SSDs [31, 196, 198, 199] and the substituted information allows them to sense stimuli and do specific tasks and sensing stimuli that are normally only available visually. These include for example: walking and avoiding obstacles [32, 131], finger maze learning [66], recognizing routes [110], navigating a maze [30], identifying the direction of motion [142, 198], recognizing body postures [195], reading words [196] and numbers [1].

Participants often respond to sensory substitution very enthusiastically and emotionally [8, 9, 102] (but see also Sect. 5.3 *Why is SSD use not widespread*). For example, when a flame was presented for the first time via the TDU to one of our CB participants, the tingling sensation on the tongue provided by the electrodes lead him to exclaim "oh! That is what fire *looks* like!."[1] Participants become so emotionally attached to their new sense (*visuo*tactile in this case) that removing access to it results in a feeling of loss. The resulting embodiment of SSD stimulation is perceived as an extension of the senses, not an outside apparatus [215].

Using an auditory SSD, several LB participants liken their sensations, after using this device for several years, to that of vision. Several authors refer to this experience as an "acquired synesthesia" [220]. Synesthesia is the phenomenological merging of one or more attributes from one sensory modality to another; for example, many synesthetes report sensing specific colors linked to specific musical

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[1] The reader is referred to a film produced by Discovery channel on the various abilities developed by CB and LB participants using the TDU. « The Plastic Fantastic Brain » https://www.youtube.com/watch?v=IzmZArOryGk&t=5s.

tones [63, 96, 140, 209, 229], or colors being associated with the imagined perception of a geometric form [33]. The experience of SSD stimulation has been linked to synesthesia because of the phenomenological attribution of visual properties to tactile or auditory stimulation [168, 221]. There are certain differences, however, between synesthesia and SSD perception. Synesthesia is an innate automatic process where the individual cannot help but perceive a merging of the senses, whereas the SSD perceptual process is an active process at first. The user must first learn to interpret the tactile or auditory sensory signal from the SSD as a new sense, and after training this process becomes automatic.

One could argue that learning to see is not an automatic process either; it is active. Just as one must learn to use an SSD, we do not automatically know how to interpret photons of light hitting the retina, vision is also an active learning process achieved through trial and error. Thus, it is possible that synesthesia is also an acquired process resulting from visual training.

We argue that the information provided by SSDs is an *amodal* task-dependent perception. The information extracted from SSDs through its active use is abstracted from the modal source (auditory or tactile) to form an *amodal* representation.

5 Sensory Substitution and Navigational Abilities of the Blind

Recently, there has been an increase in the advent of technological aids (for review see [89]) and SSDs (for review see: [133]) to help blind or visually impaired people navigate. Research in laboratory settings has demonstrated the potential level of spatial abilities that blind people can display when using SSDs [30, 51, 82, 110, 187, 190, 194]. For example, early research with the tactile visual sensory substitution (TVSS) demonstrated the "visuo"-motor abilities of the blind in tasks like batting a ball, identifying the source of light and recognizing shapes [9]. Blind people can have rapid and precise reaching movements using modern SSD's [120], and recognize various geometric forms [173, 171], complex images [6, 143, 111], and even the direction of moving stimuli [142, 170, 198]. Blind people can even complete complex tasks such as recognizing body postures [4] or facial expressions [18, 109].

It is noteworthy that vision conveys a vast amount of information instantly whereas SSDs cannot. Currently, the lack of temporal and spatial resolution of SSDs does not allow for the transfer of the complexity and richness of visual information with the same speed and accuracy [40, 191]. Instead of trying to convey the entire complexity of the visual information, some research with SSDs has focused instead on understanding and improving the way specific aspects of vision can help with navigation [30, 32, 110, 187, 190]. These specific aspects can be divided into those improving locomotion and those assisting in wayfinding.

Navigation is composed of both wayfinding and locomotion tasks [150]. *Locomotion* involves the ability to negotiate a path around obstacles, while *wayfinding* involves the more complex navigation of large environments [125]. Whiles both are made easier by visual input [141, 163, 162], locomotion and wayfinding involve different components of decision-making, and demand different skills [150]. Furthermore, they require different aspects of visual information. For example in locomotion tasks, vision is used to update distance information with the obstacle [163, 162]. In wayfinding tasks, vision helps by spotting landmarks that help the navigator situate its relative position in an environment [53, 141]. In order to be useful navigational aids, SSDs should be geared to answer the specific demands of both locomotion and wayfinding, to convey the specific information needed for both tasks.

5.1 Sensory Substitution Devices (SSD) and Locomotion

In locomotion tasks, the important aspects of the visual information are those that enable us to detect the presence, size, position, and distance to an obstacle that is in the path, as well as the basic geometry of our environment. Several SSDs are capable of sending this type of information. With a visuotactile SSD (the TDU), CB subjects outperform sighted blindfolded participants in a high contrast, life size obstacle course [32]. All participants had more difficulty stepping over an obstacle, than going around it. Using a depth to audio SSD (the EyeCane), Buchs et al. [17] tested obstacle negotiation and reported in their subjects the same difficulty in stepping over obstacles. Blindfolded participants using the EyeCane virtually performed better than another blindfolded group using a white cane, demonstrating that SSDs can be more efficient and can convey a wider variety and more complex information than a white cane alone. These studies show it is possible for blind people to learn how to use SSDs for locomotion. Now that this demonstration has been made, an effort should be made to demonstrate their usability in real world settings. Furthermore, the appropriate comparison for a device that attempts to mimic vision resides in the use of a visual control group, which is lacking in the studies mentioned. Another interesting comparison that should be made systematically when testing SSDs is with vs without the device. Many people who are blind have developed effective ways (using a guide dog or a white cane) to navigate. New devices should be systematically tested against the preferred means of locomotion of participants. Future research with SSDs for locomotion needs to be weary of ecological validity, perhaps trying them in a simulated street environment, and compare results with the appropriate control groups, using vision.

5.2 Sensory Substitution for Wayfinding

Lost in a foreign city, the ability to see from afar a building passed along a route can greatly enhance your chances of being able to retrace your steps. In this example, the building can constitute a landmark, an easily remembered and sometimes visible cue to help you find your way. In wayfinding tasks, the most important aspects of vision are those that help convey one's position in the environment. Landmarks are an important source of positioning information [79]. Images of landmarks at decision points along a route are better remembered, and elicit a greater BOLD signal in the retrosplenial cortex (RSC) than those not at decision points along the route [185].

SSDs can transfer landmark or positioning information: for example, the FeelSpace or NavBelt) indicates the magnetic North from a compass via vibrotactile stimulations on a belt that are updated with the wearer's movements [101]. Researchers found that after several weeks of training, late blind participants improved on a pointing task, maintaining a sense of direction over long distances, and finding shortcuts in familiar environments [101]. After participants have learned the SSD code, the acquired new perception is "embodied," which not only helps them select more efficient routes (i.e., shortcuts) during navigation, but also creates the feeling of a "new" sense [102].

Blindfolded participants in a maze can even remotely navigate a robot using tactile cues as landmarks [187]. In a virtual reality task, CB participants not only learned to navigate different routes but also recognize them [110]. In another study using virtual mazes, participants using the EyeCane outperformed both the no-device and white cane groups [137]. Testing the EyeCane in a real-life size Hebb–Williams maze demonstrated that CB, LB and sighted blindfolded controls (SBC) could learn to navigate with a similar performance to the sighted visual control (SVC) group [30]. Thus, many different types of SSDs can provide information that can help recognize landmarks and position the user in the environment. Why then, despite many years of research and such positive results, has SSD use not become widespread in people who are blind and visually impaired?

5.3 Why Is SSD Use not Widespread?

Participants were asked if they would ever consider using SSDs regularly. Here are some examples of their answers:

> Well, you know, I think it might be useful but I already have my dog for that! I don't think anything could ever replace my dog!

Participant OB, M, 47-years-old congenitally blind trained to use the TDU (2006).

Participant RL, M, 36-years-old congenitally blind trained to use the TDU (2007).

> This device is using up all of my concentration, it would be difficult to use it and also keep track of where I am going!

> This device is way too expensive and would require extensive hours of training. I can already get around just fine with my cane! …Maybe if people started training from a very young age… but me personally I would not buy it, not at that price.

Participant BD, M, 34-years-old trained to use the TDU, (2008).

> I would love to be able to use this device to get around the University! It would help me find doors for my classes from further away… I wouldn't have to worry about hitting people in the legs

Participant DS, F, 27-years-old trained to use the EyeCane (2014).

In spite of ambitious aspirations, impressive achievements, and the fact that some devices have been available for several decades, very few devices have found their way into the hands of blind people for everyday use, and none have become widespread [55, 124, 133, 191]. There is a high rate of abandonment of assistive technology by users [164], and even the most used SSD, the vOICe, only has a few hundred regular users around the world.

Why have decades of research using sensory substitution devices not achieved the main goal of improving the quality of life of people who are visually impaired and blind [122]? We identify several problems with the current forms of sensory substitution (Box 1) and promising approaches that are attempting to circumvent these problems. In order for devices to be generally accepted they must be made available at a very low cost (or even free of charge), and attempt to meet the specific needs and preferences of blind people when using SSDs [81].

The majority of SSDs for navigation present several problems [4]. In box 1, we discuss results from the four main SSDs used in navigation tasks: The tactile visual sensory substitution (TVSS) system [187], The TDU [32, 110], The EyeCane [133, 135, 17, 30] and the NavBelt [101].

Box 1

The Learning Problem: Most, but not all SSDs require many hours of practice and training [32, 110, 143, 171, 197]. SSD training can sometimes involve elements that are very different from the ones people learn in orientation and mobility training. For example, if the sensor is placed on a pair of eyeglasses, the user must make many head movements to adjust the angle of the field of view of the camera. By contrast, orientation and mobility (O & M) training encourages keeping the head straight [89]. Learning skills that are in contradiction could impair previously acquired mobility skills and discourage new potential users from using SSDs. The fact that people who may be interested in using SSDs for navigation need to acquire new skills to navigate, when many of them have already learned to move around efficiently using a guide dog or a cane, may make it difficult for them to see the advantages of using SSDs.

The Standardization of Training Problem: There seem to be as many tasks involving SSDs as there are publications in the field, each article developing a new task to fit its methodological needs. There are no clear guidelines for training paradigms with SSDs. The lack of standardization of the tasks makes it hard to compare the devices in terms of efficiency. Recently, a standardized version [154] of the obstacle course we used to test locomotion in the blind [32] can help resolve some of these issues. Standardization is the establishment of a set of controlled parameters against which we can test the efficiency of SSDs. For example, a strict set of controlled obstacles should be used to test these devices. Nau et al. [154] aimed to establish this set of contingencies by regulating the size and shape of obstacles in an obstacle course for all SSDs so that we may compare them to one another. Using standardized testing procedures in obstacle avoidance, i.e., locomotion [32, 154], or navigation, (wayfinding like the Hebb–Williams mazes [30]) will help us understand how to develop better devices geared toward specific tasks. Most SSD training programs do not take into account the motor aspect (see Sect. 2). This aspect is crucial and must be taken into consideration when devising a standardized training protocol for SSDs. The vOICe (https://www.seeingwithsound.com) (see also: [177]) and EyeMusic (http://brain.huji.ac.il/launch/StepByStepHeb/see) do have certain training exercises on their websites to help users learn to recognize objects, but this does not compare to the extensive training people receive when learning how to use the long cane in O & M, for example. Researchers must direct their attention to optimizing the learning process for SSDs perceptual training in order to help guide potential users through the steps needed to interpret the information from the device.

The Temporal Problem: In order for an SSD to be useful in navigation, the image in the user's surroundings needs to be presented and interpreted in real time. Many forms of auditory-based SSDs translate the image into sounds using the temporal aspect as the left-right translation of the image. This creates a delay in the presentation of the image to the user (though see [220] for how this can be solved with enough experience, similar to foveal vision). Other forms of tactile based SSDs such as the TDU transmit the image in real time, but because of the complexity of the information, the interpretation of the stimulation is often delayed.

The Dissemination Problem: Many blind or visually impaired people are not informed of the SSD technologies available today. More effort should be made to disseminate the results of SSD scientific research to the first ones concerned by such forms of research. Furthermore, a lot of the scientific journals (where this type of research is published) are not always easily accessible for the blind, including the presentation of graphs and figures.

Peter Meijer, a scientist based in the Netherlands, and the inventor of the vOICe system has made noticeable and praiseworthy efforts in this direction by regrouping the most recent literature on SSDs, brain plasticity and rehabilitation (https://www.seeingwithsound.com/), and making his website easily accessible for blind and visually impaired individuals.

The Cognitive Load Problem: The cognitive load problem concerns the complexity of the algorithm used to generate the stimuli, which ultimately needs to be learned by the user. The more complex the interpretation of SSD information, the more difficult the completion of the sensorimotor loop described in Fig. 2. This makes it cognitively taxing to simultaneously interpret the SSD's information and accomplish a task that demands attention. Most forms of SSDs require great concentration, even in the case of trained users [122]. Reducing SSD information (from whole scene information to more precise forms of information) could help improve this issue.

The Orientation Problem: This problem concerns localizing objects in space accurately using SSDs. The direction of the SSD information is often confusing and although participants can sense that objects are in the field of view of the camera or sensor, they often report being unable to tell where exactly the sensor is pointing in the environment. For example, in the case of head-mounted camera systems (such as the TDU, or vOICe), it becomes quite difficult to understand the direction the camera is pointing to, since it is not fixed (i.e., it can be pointed up or down). The sensorimotor loop comprises therefore an additional error that makes learning the code more difficult. In order to localize an object in space accurately, the field of view of the camera or sensor of the SSD must be constant. Proper training in remapping must be optimal to achieve the appropriate distal attribution of the moving stimulus.

The Depth Problem: Older generation SSDs do not code for depth. The lack of depth information makes it difficult to detect ground level obstacles and step over them [17, 32]. The newer devices do incorporate some aspects of depth information. The EyeCane, for example, is entirely based on the translating depth information into vibrations and sounds [131] (see Fig. 1d, e). Another device that uses laser projection patterns allows 90% accuracy in detecting potholes [174].

The Contrast Problem: Many SSD's, such as the TDU, only work under optimal contrast conditions. Under any other (naturalistic) settings, or dimly lit situations these devices will not work very well.

The Resolution Problem: Most SSDs down sample the resolution of the image in order to send it through another modality. This down sampling of the image results sometimes in very low resolution. The best visual-acuity available with a 10 × 10 grid of the TDU is still inferior to the standard of vision used in rehabilitation. The vOICe has a better resolution than most SSDs, but takes longer to interpret. This loss in resolution of the image makes it difficult to recognize details of a scene. Most SSDs, however do enable a zoom in factor (both the TDU and vOICe have this option). A recent study explored this question by testing the zoom in factor in the EyeMusic SSD, and found that participants are able to recognize facial features of cartooned identities [18].

The Cost Problem: Although the cost to make most SSDs is minimal, the companies that make and distribute them usually inflate the sell prices. This is probably due to the long research and development phases most SSDs go through. Some companies or laboratories that develop SSDs try to keep their cost down by basing their programming on already existing devices, such as exploiting the hardware on smartphones, instead of creating dedicated hardware.

Some attempts have been made to overcome these problems. For example, the EyeCane is easy to use and require little training but has a very low resolution. In sharp contrast, devices that offer a higher resolution comprise very complex coding that make them more difficult to use and require therefore many hours of training (for example, the vOICe [145]; and the EyeMusic; [1]). The EyeMusic has implemented many of the solutions suggested here: it is available for free, and is downloadable as an application for smart phones. The EyeCane is still in development but researchers have already demonstrated its use in judging distances in the real [131, 137], and virtual world [132, 133], detecting and avoiding obstacles [17], and navigating through a real-life-sized maze [30]. It uses the same strategies as a white cane, making sweeping movements from side to side to scan the environment. Blind people trained with the white cane can build on existing training to use the EyeCane [135]. We predict that these devices may have a huge impact on the lives of blind people in the next few years, but in order for this to happen they must meet the criteria described above and the particular needs of blind people when using SSDs.

6 Neural Structures Supporting Navigation

Navigation involves the coordination of various neural structures (for review in humans see: [11, 228]; for review in animals: [144]), supporting perceptual [116], memory [22], proprioceptive [227], and motor systems (for review see: [205]). We describe these structures in the next few sections, first in animals and then in humans.

6.1 Animal Studies

In animals, the posterior parietal cortex comprises maps for places in terms of their order on a route [156, 155]. Other structures also play a supporting role in navigation, such as the caudate nucleus that integrates spatial behavior with motor behavior [222], and the parahippocampal gyrus that possesses view-responsive neurons to spatial scenes [179]. The hippocampus and entorhinal cortex have several different classes of neurons [20, 19] that deal with a slightly different aspect of navigation, such as place cells [91, 159], head-direction cells [206, 225], grid cells [78]; for review: [151] and boundary/border (or vector cells) [20, 119]. There is evidence in bats that their ability to fly enables a multiscale 3D acquisition of spatial information cells [67]. Multiscale maps are composed of three-dimensional head-direction coding cells in the bat brain [61]. Lesions in hippocampal, frontal or parietal cortices impair the ability of rats to learn and retain a spatial layout [39]. Only lesions to the hippocampus specifically impair spatial navigation [72]. Furthermore, goal locations are encoded via place cells as vectors to local targets in a maze [65]. These studies highlight the specific role of cortical and subcortical areas in navigation.

This complex navigation system is mature very early on in development. The place cell network of the hippocampus displays adult-like properties as soon as exploratory behavior emerges [152], and head-direction cells are functional even before eye opening in the rat [203]. These results suggest that environment-based cell networks develop independently of vision. What are the brain regions that mediate navigation in Humans?

6.2 Human Studies

Spatial processing functions underlying navigation in humans are believed to be generally similar to those encoding spatial memory in animals [46]. Using, a slow event-related fMRI paradigm, Spiers, and Maguire [193] broke down the different steps involved in navigation in humans, clarifying the role of the different regions initially identified in animals. They found a complex choreography of areas and cellular populations involved in both transient and sustained activity during navigation [193]. In this section, we review the specific contribution of these distinct brain regions involved in different forms of navigation strategies.

Traditionally, spatial memory and navigation have been associated with the hippocampus [126, 127]. In the sighted, the link between hippocampal volume-and navigation-related tasks are well established. In a classic MRI volumetric study, Maguire and colleagues [129] investigated volumetric differences in the hippocampus of humans with extensive navigational training. They measured the different segments of the hippocampus (anterior, posterior or body) and showed that the training-induced plastic changes in highly trained navigators resulted in a volumetric augmentation of its posterior segment [129]. Conversely, hippocampal volume reductions are associated with impaired spatial memory [76]. Several different kinds of neurons supporting spatial behavior have also been found in humans [84]; *places cells*: [54]; *grid cells*: [46, 97]; for review on place and boundary cells: [14].

Recently, it has been shown that the anterior part of the hippocampus shows increased activation bilaterally at the start position and near to the exit of a maze [214], whereas the posterior segment is sensitive to borders or boundaries, like being near a wall [47]. The different segments of the hippocampus (Anterior, posterior and body) may actually complement each other by competitive activation/deactivation during navigation [50]. For example, the anterior hippocampus is sensitive to encoding of spatial information, while the posterior is active during retrieval [75, 94].

Two main spatial strategies have been identified [107, 108]: egocentric (a representation that is relative to the observer), and allocentric (a representation that is based on the relative position objects, landmarks or places have in relation to one another). Egocentric strategies comprise acquiring route knowledge, and categorical knowledge. Route knowledge is when spatial knowledge is acquired from navigating a route, and categorical knowledge is when spatial relations are learned between locations [159]. Allocentric strategies are composed of survey knowledge, and coordinate spatial learning [223]. Distinct brain regions mediate egocentric and allocentric navigation strategies [38], and different neural structures play different roles for learning an environment [23]. The posterior parietal lobe has a role in egocentric spatial processing (for review see [19]). The medial part of the posterior parietal lobe seems to be involved in the processing of movement through immediate space with the lateral part involved in processing movement through non-immediate surroundings [192]. The striatum, in particular the caudate nucleus, is critical for memory of places [15]. The retrosplenial cortex bilaterally [94] is believed to update reference frames when navigating [95], and shows increased activity during spontaneous route planning, which necessitates updating topographic information [192]. The parahippocampus is involved in encoding the local scene and generating a cognitive map ([2, 57–59, 128] (for review on RSC and PPA see [56, 60]). Additionally, the visual cortex may also play a direct role in navigation. Recently, Dilks and collaborators [45] described an area around the transverse occipital sulcus (coined the Occipital Place Area, OPA) that plays a role in representing boundaries (i.e. edges, walls, and other delimitations in the environment) [99], and the local elements of a scene [100].

These studies show that navigation is composed of many different elements that rely on the interaction of several distinct brain regions. The question remains, however, on the contribution of these brain areas when vision is impaired such as in congenital or acquired blindness.

7 Theories of Spatial Representation in People Who Are Blind

Despite many demonstrations of navigational abilities in blind people, some theorists believe that they have deficiencies in some aspects of their spatial representations. Although certain changes are apparent when considering the spatial sense of blind people, we argue that those differences are task specific, due to the limited access to spatial information, rather than due to deficiencies in spatial representations. That is, the deficiencies exhibited by blind people during navigation are due to the lack of access to spatial information, not to an inherent inability to represent space. There is no apparent consensus about how blind people represent space or their specific navigational strategies [186]. Studies report differences between congenitally blind and sighted individuals concerning their ability to represent space, some reporting deficiencies [24, 25, 73, 104, 213], others supra-normal abilities [37, 48, 64, 74, 121, 178, 216]. Can these apparent contradictions be reconciled?

The deficiency theory argues that the lack of visual experience creates a misalignment of auditory spatial maps and, consequently, a deficiency in spatial representations [73]. In this view, vision is needed to calibrate space for the other senses. Since vision plays an important role in auditory spatial map development [105], this theory argues that vision is required to construct and calibrate auditory spatial maps. This argument is supported by findings that early blind individuals are impaired in the encoding of audio motion in the vertical axis [62], and of auditory spatial relationships between sound sources [73]. Early blind children also show a deficit on a bisection task between sound sources [213], and on simple auditory localization tasks [24]. Auditory and proprioceptive skills of both early blind children and adults are also compromised [25].

Other studies find, in contrast, that congenitally blind people are better than their blindfolded counterparts at locating a sound source, and have better use of monaural cues [118, 216]. Congenitally blind people have also been found to have superior pitch discrimination [74]. Using an SSD (the TDU), CB individuals have a finer *visuo*tactile acuity [31, 199], are better at recognizing routes [110], and can negotiate and recognize obstacles better [32] than their blindfolded counterparts. The supranormal abilities of CB are attributed to the recruitment of the occipital cortex [6, 7, 36, 37, 171, 218] and other visual structures for motion [182].

This contradiction between both sets of results (deficient versus supranormal spatial representations) can be somewhat reconciled. There appears to be a trade-off between localization in the horizontal and the vertical plane; superior abilities for monaural sound localization in the horizontal plane are associated with a deficit for localizing a sound source in the vertical plane in CB [217]. Furthermore, the tasks used by Gori et al. [73] are complex and require the subjects to estimate the relative position of objects to one another. It, therefore, seems that these differences might be explained by the differences in the nature and complexity of the tasks used. In a recent review, it was argued that differences in spatial representations between sighted and blind individuals, are either convergent, cumulative, or persistent [186]. Convergent differences in spatial representations mean that although it may take longer for blind people to acquire spatial information, the difference between the blind and the sighted decreases as the blind gain knowledge about the environment. The cumulative model of differences in spatial representations between the blind and sighted, however argues that the discrepancies in spatial knowledge will increase with spatial experience. In other words, the blind will never be able to gain the amount of spatial knowledge held by the sighted because the differences between these groups only increases as they gain experience of their environment. The persistent model proposes that spatial knowledge differences remain constant between the blind and sighted. Deficiency theorists argue that the differences between blind and sighted individuals must be either persistent or cumulative. We propose that this difference is convergent and with the substitution of the right aspect of spatial information (such as with SSDs), blind individuals can learn an environment as efficiently as the sighted people, and perform as well as the sighted in certain spatial tasks. This is possible because spatial representations are *amodal* in nature and because of the plastic adaptation capabilities of the brain.

7.1 Amodal Representation of Space

We suggest that the successful performance of blind individuals in many spatial and cognitive tasks indicates that the representation of space can be amodal. Spatial information is acquired from both visual and nonvisual sources that combine to form a multimodal representation of space [70, 113, 207]. Spatial information can be gathered from other senses besides vision, even if vision is the best-adapted sense to acquire spatial information. Spatial representations can also be formed using extended-touch: poking a probe, a 1–2 m long pole, to gather information about an object that is beyond arm's reach [69].

A blind person might be able to acquire the same information about the environment using a probe, but will probably take longer than a sighted person acquiring the same spatial information visually. That is because vision collects the spatial information instantaneously. It is possible to experimentally match the information a blind person gets through the tactile or auditory modalities to those gained through vision by either manipulating the environment (deteriorating the quality of visual information, for example), or increasing the amount of knowledge the tactile or auditory senses can gain (with SSDs for example). When spatial information is matched through different modalities, CB can learn spatial representations as well [30], and in some instances even better than the sighted [32, 122, 226]. It is the lack of access to spatial information through the use of visual cues that accounts for blind people's difficulties navigating [28, 64, 123, 148, 161, 208, 212].

Studies in perceptual learning [169], and mental scanning of pathways [92] led to the conclusion that the representation of space does not require vision [88, 93]. For example, blind people can learn spatial maps through the sense of touch [66, 208, 210, 211], or from virtual reality training [136, 201], and generate accurate representations of space, which can later be used to navigate [115, 136, 146, 202]. Both blind and sighted participants can access amodal, functionally equivalent representations of space, although they are based on different sensory inputs [122]. Further evidence for the amodal representation of space comes from studies exploring the neural correlates of navigation in the blind with or without SSDs. We review that literature in the next section.

7.2 Neural Processing of SSD Information

One of the most fascinating aspects of users trained with SSDs is their recruitment of cortical "visual areas" [6, 171, 184]. This training-induced recruitment has been linked to increased tactile [3, 52] and auditory [44, 80, 118] sensitivity in response to sensory input and environmental demands.

Before training (Fig. 1), the SSD stimulation is incomprehensible to the user, and will recruit modality specific and prefrontal areas in the brain [171]. After training however, this stimulation has taken on visual properties and users feel a sense of embodiment concerning the SSD signal. In CB participants this shift in interpretation of the signal is correlated with the recruitment of cortical areas typically associated with vision [6, 171]. This recruitment of the visual cortices depends on an active interpretation of the SSD stimulation [153], as described in Sect. 3. In other words, our understanding of the sensory information during training shapes our cortical processing of it.

The impact of training-induced plasticity in the blind seems to be twofold. First, as mentioned above, SSD tasks recruit the occipital lobe and prefrontal areas demonstrating that these areas are multimodal. Second, there is a task-specific activation of similar regions in blind and sighted participants with completely different sensory inputs. It has been shown consistently that the brain treats the information from SSDs as "*vision*" in a task-specific way, sending the information to highly specialized cortical treatment centers. The "visual cortex" of congenitally blind people is functionally active and can receive information from different senses [26, 165, 171, 183]. The SSD information is transmitted to the appropriate nodes of the brain according to the task.

Visual processing is generally segregated into two separate and parallel pathways in humans [85, 189]. These anatomical pathways are separated into a dorsal stream that analyzes visuospatial information and a ventral stream that is responsible for processing form [71, 149].

These separate visual streams are composed of highly specialized nodes that process specific aspects of visual information. For example, motion is processed in cortical area hMT+, objects, and faces in the inferior temporal cortex [41, 204].

There are also distinct cortical nodes for body shapes [49] and even words [34]. Research with SSDs has consistently demonstrated the recruitment of specialized nodes in the congenitally blind that are task-dependent [142, 170, 173]; for review: [111]. Furthermore, using a *visual to auditory* SSD, [198] and colleagues showed that the selectivity for shape and localization in the two streams could develop in the total absence of vision after just a few hours of training.

Studies with SSDs have used specialized tasks to recruit these nodes presenting words, body shapes, and motion through touch or sounds. In CB participants, task-specific nodes that have been thus far identified include: a Visual Word Form Area (VWFA) [175], an area for recognizing body postures [195], an area for number forms [1], an area for motion [142, 170, 198], an area for shapes [173, 198], and one for navigation [110]. These areas are well known in the sighted to be involved in these specific tasks, and appear to be recruited by the congenitally blind when performing the same tasks using nonvisual modalities.

Taken together, these results suggest that not only is the occipital cortex of the blind recruited when using SSDs by an active reinterpretation of the signal, but also that the brain treats the afferent information in an amodal, task-dependent way (for review see: [176]). The functional connectivity of the visual cortex in the blind develops according to retinotopic organization, despite the total absence of vision [200]. This had led many researchers to posit that the human brain has evolved so that certain types of information are treated in specific areas, regardless of the modality, and to view the brain as an amodal task-specific machine [5]; for review see: [87]. This hypothesis implies that the brain is not particularly interested in the modality from which the information originates, but rather depends on the task it is trying to perform with the sensory input the cortex receives (for review on the integration of multisensory information in the brain see Harrar et al., Chap. 4)[2].

7.3 Neural Correlates of Navigation in the Case of Blindness and Evidence for the Amodal Processing of Spatial Information

Although visual cues greatly facilitate acquiring spatial information [53], the neural circuits associated with spatial processing include multiple sources and are not tied to a specific modality [114, 68, 207]. The parahippocampal place area (PPA) and retrosplenial cortex (RSC) are both recruited for spatial processing in blind and sighted individuals. Research on the neural correlates of navigation in the blind has been limited, until now, by the difficulty of creating virtual environments for the blind as these environments, and especially the in-scanner versions, are mainly based on optic flow. A first attempt to try and understand the impact of congenital

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[2] For more on this, please see the chapter, Harrar et al., *The Multisensory Brain,* Chap. 4 in this special edition).

blindness on the structures commonly associated with navigation was made using volumetric studies. For the sake of clarity, we have divided the information on brain correlates into *volumetric* and *functional* MRI studies. In the first set of results, the volume of a certain area can be related to its function. In the second set of results, activations of a specific area indicate its function because activations are linked to a specific task.

7.4 Volumetric Studies in the Blind's Brain

The brain of congenitally blind people undergoes massive structural and volumetric changes in all of the visual structures [111, 117, 138, 172, 188]. These volumetric changes in the blind depend upon the duration of blindness [138], and hypertrophy of nonvisual frontal and cerebellar areas suggest compensatory adaptations in blindness [117].

While the caudate nucleus is not volumetrically different between the blind and sighted, and these differences were not linked to a specific navigation task [217], the hippocampus of the CB undergoes significant changes in both the posterior [29] and anterior end ([64]; but see also [138]). While the posterior portion of the hippocampus is reduced in the blind [29], the volumetric enlargement of the anterior portion is associated with superior navigational abilities [64]. This finding was explained by the lack of visual projections from the atrophied visual cortex (for review: [157]), and the possibility that the blind may rely more heavily on other structures besides the posterior hippocampus (such as the posterior parietal cortex) for navigation. Since the anterior end of the hippocampus is not usually associated with spatial processing but rather with verbal memory [77]; but see also: [130]), congenitally blind participants may rely more on verbal representations of space (i.e., egocentric strategies), and increased demands on memory systems.

Two out of the three studies that investigated volume in the blind did not correlate volume with performance [29, 117], and the third aggregated blind and sighted populations to obtain their results [64]. Furthermore, the methods used to segment the hippocampus are arbitrary and not based on any cytoarchitectonic differences in cellular populations. The anterior, posterior, and body segmentations of the hippocampus actually comprise several different, distinct cellular populations (Fig. 3).

For this reason, we feel that the link between volume and performance in the blind has not been fully established [186]. Furthermore, the segmentations of the hippocampus that were used are based on arbitrary limits: There is no cellular basis for segmenting the hippocampi into posterior, anterior and body, rather each one of these segments is composed of distinct cellular populations (Fig. 3).

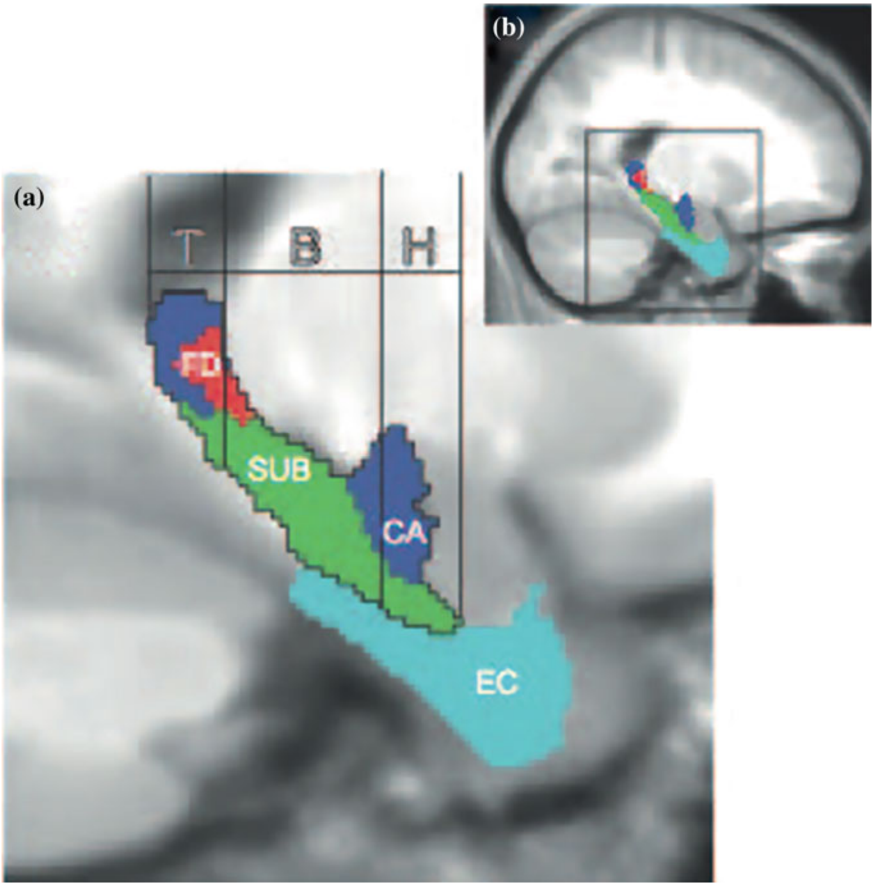


Fig. 3 *Hippocampus* (*FD* Fascia dentata in *red*, *SUB* subiculum in *green* and *CA* cornu amonis in *dark blue*), hippocampal area (*HATA* hippocampal amygdaloid transition area, *EC* ectosylvian cortex in *light blue*)

7.5 MRI and EEG Studies on Spatial Representations in the Blind

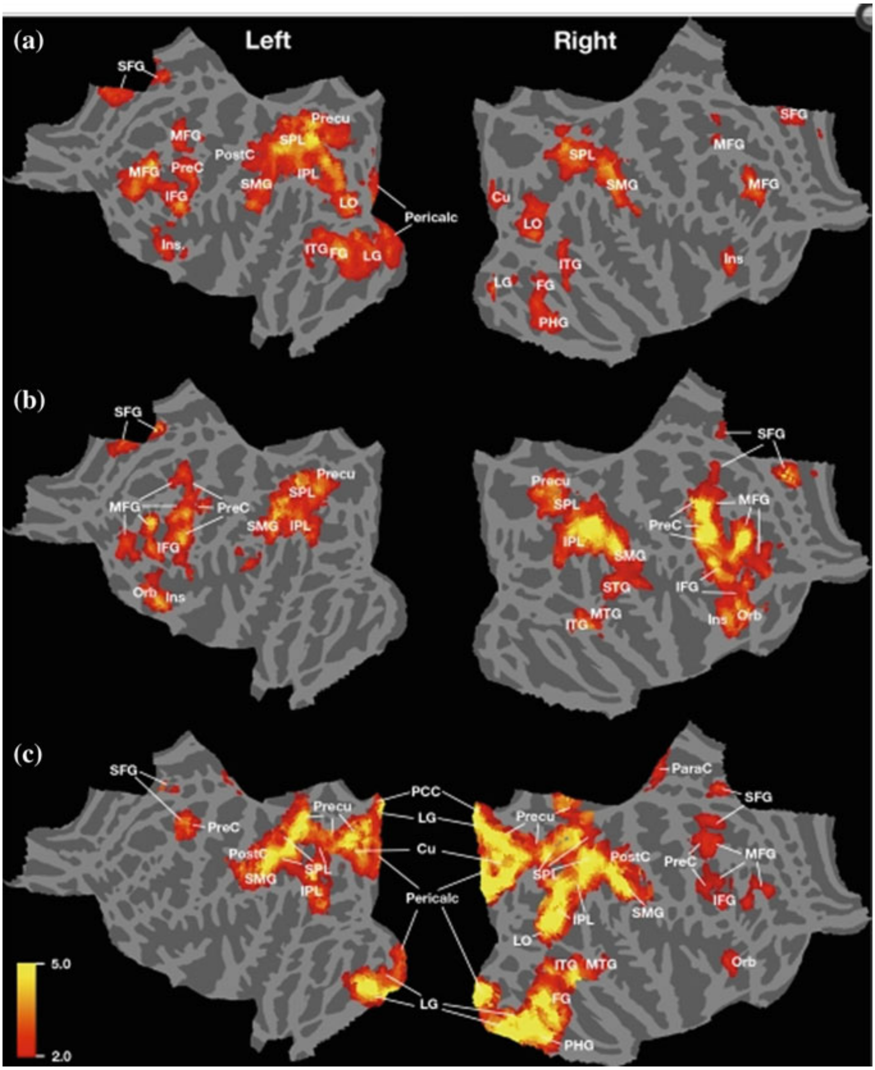
Research has explored the neural correlates of navigation in blindness in an attempt to disentangle the volumetric results mentioned above. We previously proposed a task whereby blind people had to learn how to recognize routes using a visuotactile sensory substitution device that translates a visual image into electrotactile stimulation applied to the tongue (i.e., The TDU: see Sect. 3 on sensory substitution) [110]. Participants had to learn to navigate these routes in virtual environments, and then recognize those routes while in a 3-T scanner. These results (Fig. 4) enabled the identification of a neural network involved in route recognition in the blind

Fig. 4 Neural correlates of route recognition in blind and sighted subjects. Brain activation ▶ patterns during route recognition using the TDU compared to a visual control paradigm. *Red* and *yellow voxels* represent clusters of significant BOLD signal increases during the route recognition compared with random noise presentation, superimposed on cortical flatmaps. (*A*) Results of blind participants, showing activation of occipital and posterior parietal cortices, precuneus, fusiform gyrus, and right parahippocampus during route recognition with the TDU. (*B*) Blindfolded sighted control subjects did not activate the parahippocampus or occipital cortex, but they activated the posterior parietal cortex and the precuneus. (*C*) Sighted control subjects, performing the route recognition task visually, showed strong bilateral BOLD increases in the occipital and superior parietal cortices, the precuneus, fusiform gyrus, and right parahippocampus. *Cu* cuneus; *FG* fusiform gyrus; *Ins* insula; *IFG* inferior frontal gyrus; *IPL* inferior parietal lobule; *ITG* inferior temporal gyrus; *LG* lingual gyrus; *LO* lateral occipital; *MFG* middle frontal gyrus; *MTG* middle temporal gyrus; *Orb* orbital gyrus; *Paracent* paracentral gyrus; *Pericalc* pericalcarine sulcus; *Precent* precentral gyrus; *Precun* precuneus; *Postcent* postcentral gyrus; *SFG* superior frontal gyrus; *STG* superior temporal gyrus; *SPL* superior parietal lobule; *SMG* supramarginal gyrus

(Fig. 4a), for the first time [110]. Two control groups were used for this study: Sighted blindfolded participants (Fig. 4b) who used the TDU to do the task, and sighted participants who were allowed to see the routes (Fig. 4c), thereby using vision to perform the same task. The structures activated in the congenitally blind brain (Fig. 4) during this route recognition task were the same as those activated in the sighted participants doing the same task visually: the parahippocampal gyrus, posterior parietal cortex, and the visual cortex (Fig. 4a, c). In contrast, the sighted blindfolded participants recruited a different network of brain regions that did not include the parahippocampal gyrus or the visual cortex [110] (Fig. 4b). The congenitally blind brain does recruit visual areas for tactile [21, 35, 171, 180] and auditory tasks [6, 167], whereas a brain that is wired for vision (blindfolded controls) does not recruit primary visual areas for nonvisual tasks. This functional rewiring enables the recruitment of the same cortical network used for spatial navigation tasks in CB as in sighted subjects.

A study using tactile mazes (accomplished by placing the finger in a hand maze) found that active navigation could recruit the hippocampal formation in congenitally blind subjects [66]. In addition, parietal and occipital areas were also activated during this tactile maze solving. It is possible that the lack of activations in a passive route recognition task [110], compared to the hippocampal recruitment in the active finger maze navigation [66] reflects the fact that the hippocampus strictly processes active navigation in the CB, and not passive recognition of previously learned routes.

The recruitment of the hippocampal formation was also found in congenitally blind individuals making spatial distance judgments with an audio-tactile device [27]. Participants were asked to judge the distance of an object that they could detect using a device translating distance into tactile and auditory pulses. In addition to the hippocampus, the inferior parietal cortex and parts of the right occipital cortex were also activated in the congenitally blind for this task [27]. Chan and



colleagues explain that integration and binding of auditory features to distances are responsible for the hippocampal activations. Sighted blindfolded participants did not activate this network when doing the same task, rather they only recruited parietal areas. These studies conclude that the blind use the same networks to navigate as the visually sighted, while the sighted blindfolded population recruits a different network. They also suggest that mechanisms of brain plasticity can recruit the visual cortex in the blind to accomplish navigation -related tasks.

During imagined locomotion, congenitally blind participants recruited multisensory vestibular areas in the posterior insula and superior temporal gyrus, but did not show activations in parahippocampal and fusiform regions [42]. In a follow-up study by the same group, imagined locomotion and stance (standing) did activate the hippocampus [43]. Further, during *imagined* locomotion, widespread activity was found in the right parahippocampal gyrus in both sighted and blind individuals, although compared to sighted controls, blind subjects showed less activity in the right dorsal parahippocampal region [98]. These authors concluded that the parahippocampal and fusiform gyri, which are connected to visual cortical areas, are important for visually guided locomotion and landmark recognition during navigation.

Sighted blindfolded participants recruited both PPA and RSC for visual and haptic exploration of a 3D spatial scene [226]. These results suggest that these areas are amodal, meaning that they are more concerned with the nature of the task at hand (navigation) and less with the modality (visual, auditory or somatosensory). Additionally the RSC, transverse occipital cortex and PPA were more strongly activated by landmarks (large non-manipulable objects) for both congenitally blind and sighted participants (blindfolded and visual group) in an auditory size judgment experiment, [86]. In this task, participants had to judge the size of an object (small tools, large manipulable objects and animals) based on the auditory cues. The authors concluded that these regions did not need visual experience to develop a preference for large landmarks (i.e., a stronger activation in the landmark condition than the other conditions). Furthermore, using EEG, Kober et al. [106] showed a significant occipital activation during a motor imagery task in mostly late blind participants, which is not the case with the sighted. The authors confirmed that the blind recruit the visual cortex to navigate [110].

8 Conclusions

In this chapter, we have reported and discussed the most recent advances in sensory substitution and the neural correlates of navigation in the case of visual impairment or congenital blindness. We have suggested that the sensorimotor loop involving SSDs is the basis for training-induced plastic changes in the brain. Indeed, phenomenological reports of late blind people using SSDs liken it to what they remember of vision. Furthermore, the brain of CB seems to treat this information in amodal, task-specific highly specialized brain nodes. This cortical plasticity enables the learning of an SSD code and the embodiment of the resulting perceptions. This embodiment, in turn, enables participants to accomplish many behavioral tasks such as navigation. The neural structures that support navigation and SSD use in the CB and LB brains indicate that spatial information is amodal and that the brain treats spatial information in a task-specific way. Future studies should place an emphasis on testing SSDs in naturalistic settings and investigating the neural correlates of active navigation in the blind.

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Visuo-Vestibular and Somesthetic Contributions to Spatial Navigation in Children and Adults

Irini Giannopulu

1 Introduction

Infants come in the world with a neural system to see and perceive what is around them, but their visual structure is poor, the most primary functions are immature. Their visual development is characterised by critical periods in many notable visual functions, and by extensive learning from experience and increasing control over the visual mechanisms. Ventral and dorsal systems authorise them to transform visual information into cognitive representations associated with object's recognition and location in the egocentric space all along static and dynamic motion activities. Visual areas serving dynamic motion process allow infants to harmonise visual information with vestibular information to discern their own body position and movement in space. To analyse rotational and translational movements, the vestibular system is structurally composed by the semicircular canal system, which displays angular accelerations; and the otoliths, which display linear accelerations. The vestibular system sends signals primarily to the neural structures that command eye movements, i.e., vestibulo–ocular reflex, which is required for clear vision, and to the muscles, i.e., proprioceptive system, that commands posture, which is necessary to keep infants upright. Together with the visual information, bilateral vestibular organisation not only contribue to the equilibrioception in three axis (sagittal, vertical and lateral) at cortical and subcortical levels, but it is directly and indirectly involved in internal representation of the body, navigation, memory, and orientation at cortical level.

The internal representation of the body is related to the internal representation of the verticality (e.g., [76]). Behavioral findings seem to be coherent with neurophysiological data showing that vestibular, somesthetic, graviceptive afferents and

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the Bayesian probability theory established that the perception of ego motion direction relies on integration of multiple sensory cues. All these afferents which are interconnected in cortical and subcortical levels are transformed into representations that contribute to the internal representation of the body. This latter can be thought as an egocentric reference providing spatial navigation and orientation. In active or passive locomotion a large range of sensory information can potentially provide feedback including visual, vestibular and somesthetic (proprioceptive and exteroceptive-haptic) inputs. Balance and locomotion are highly interdependent: balance authorises children to walk safely, locomotion improves the control of balance (e.g., [130]). Balance and locomotion provide the ground of spatial navigation towards object and locations. Visuomotor, vestibular, and somesthetic abilities give children and adults the possibility to explore actively or passively the space. Cognitive factors potentially influence ego motion in children and in adults.

Linear sagittal ego motion seems to be determined by cognitive and vestibular components. More particular, the intra-individual variability of vestibular sensitivity between sagittal and vertical axes would explain the intra-individual variability of the ego motion sensitivity between both axes (e.g., [47]). The inter-individual variability of vestibular sensitivity along the vertical axis would explain the inter-individual variability of the ego motion sensitivity along this axis. Exclusively cognitive variables, such as the plausibility or implausibility of ego motion is capable of modulating the ego motion sensitivity. Visual attentional factors and memory process specially those associated with visuospatial working memory can be considered as decisive elements of ego motion in real as well as in virtual environments. Visuo-vestibular and somesthetic interactions together with cognitive factors strongly contribute to the ego motion. Both bottom-up and top-down ego processes act together in a synergic way to harmoniously perform spatial navigation. It seems that the brain consistently weights multiple information that is on the basis of spatial navigation. Under passive and active navigation, the perception of ego motion is assisted by covariant signals coming from visual, vestibular, and somesthetic systems.

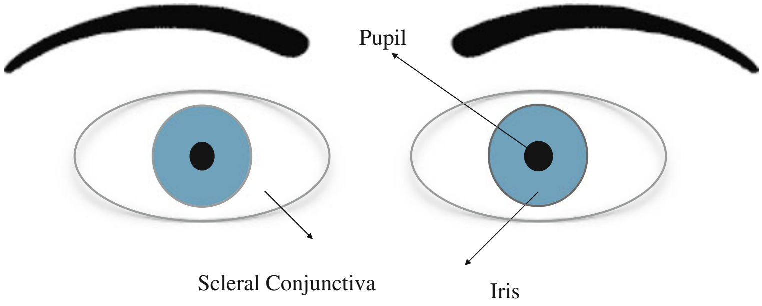
Starting with the visual development, we will continue with the analysis of vestibular system and its relationship with the visual, somesthetic (proprioceptive, exteroceptive-haptic) systems. Then the relationship between the integration of information and internal representation of the body and verticality will be given. Considering the internal representation of the body as an egocentric reference providing spatial navigation and orientation, the ego motion in children and adults in space will be analysed. Ego motion in children and adults will be examined via visuo-vestibular and cognitive influences. Naturalistic prerecorded and virtual environments will be presented in studies where visually induced ego motion is discussed in relation with attentional and visuospatial memory processes and spatial intuition. The effect of visual information in spatial navigation in blind and blindfolded sighted persons is also reported.

2 From the Eye to the Perception of Visual Movement

The nervous system uses visual information of the environment in order to transform it to perception. A big agreement is known regarding how this process takes place within individual visual pathway. Visual development and perception do not follow an established plan. Irregularities in the typical development progression can have permanent repercussions on the final degree of visual functioning. Studies realised in humans (e.g., [6]) have explained that visual development and perception rely upon the visual inputs very early in life. The argument here is to give the development sequences of visual system and perception.

The eye is the peripheral organ of the visual system. Its relevant parts are optical: scleral conjectiva, iris, cornea, pupil, lens (Fig. 1a). This external architecture fashions an adaptable optical complex to transport images at the back of the eye: the retina (Fig. 1b). The visual system of the human infant is immature at birth. Studies argue that this immaturity starts at the retina and more particular in the fovea (e.g., [1]). In other words, young infants are inept at different performances such as eye movements (e.g., [7]), accommodation and convergence (e.g., [9]).

(**a**) external anatomy



(**b**) internal anatomy

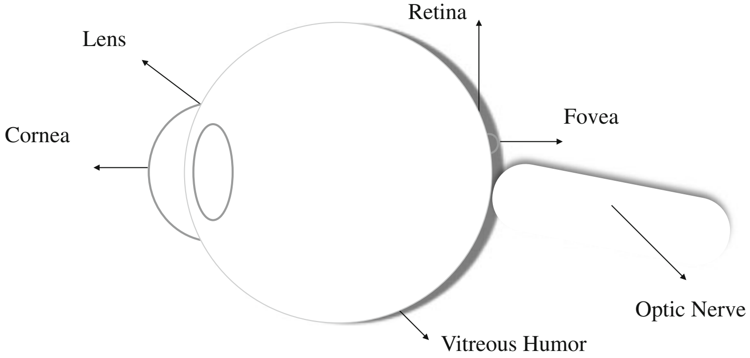


Fig. 1 Anatomy of human eye (**a** and **b**)

Studies have reported that the ability to focus an object in order to see its image depends on brain maturity. Under one month, young infants have a very bad accommodation. At four months they became good accommodators and they can correctly see objects at various distances (e.g., [9]). Functional vision also depends on how the eyes are jointly placed. Hainline and Riddell [61] put forward an inter depended relation between accommodation and vergence. Young infants who do not show evidence of varying accommodation to targets at various distances, they do not show any evidence of convergence. It has also been reported that around four months, the convergence of young infants is almost good (e.g., [84]). For both accommodation and convergence, binocular fusion is indispensable (e.g., [63]) as depends on having the ability to place (point) the two eyes accordingly when looking at objects. Following the hypothesis of Hainline [63], such ability develops early on in such a manner that as fine acuity matures, the eyes maintain to be in alignment with the extent of precision compatible with the level of spatial vision. Spatial vision itself cannot be considered without the oculomotor development.

It is of evidence that functional vision is influenced of eye movement: saccades and fixations. The most rapid eye movements, i.e., saccades, serve to point the fovea at objects that must be examined. As fovea of young infants is immature, saccadic behavior is immature as well. Surprising evidence exists that the maximum velocity and the amplitude of a saccade are very similar for infants and adults (e.g., [60]). Even if a saccade depends on object's size and nature, i.e., natural or virtual, the saccadic system appears quite mature and ready to function at early age.
A saccade is commonly accompanied by a fixation. During fixation the eyes are grasped more or less immobile in order to examine the object. Infant fixation time seems to be related to the quantity of available visual details. Many details necessitate briefer fixations that few details. The maintenance of stable fixation is difficult for young infants, as if the visual feedback about a stimulus moving rapidly across the retina leads to a refixation (e.g., [62]). Small objects are better refixed by young children than big objects. Given the above, it seems that infants possess sufficient oculomotor activity and control to provide careful investigation of static visual scenes.

The retina is placed in the back of the moving eye that is located in a moving head. To keep an image stable on the retinal fovea, the eye must rotate smoothly. Smooth pursuit is the specific ability that stabilises the moving image of a given object. Immature fovea showed poorly developed smooth pursuit (e.g., [120]). Studies made evident a smooth pursuit for salient targets at slow speeds (e.g., [132]). With the speed increases, infants use adaptive saccades in addition with smooth pursuit (e.g., [62]). The oculomotor system linked to the vestibular system, optokinetic nystagmus (OKN) and vestibulo–ocular reflex (VOR) are participating to compensate the movements of the organism thought the world and some of the associated movements of the retinal image (e.g., [34]). OKN is produced when a large portion of the visual field's retinal image shifts cruise the retina. The two eyes move as a unit following two alternative phases: slow phase and fast phase. In that case, the slipping of the image in the retina is controlled. Even if oculomotor asymmetries are presented when OKN is triggered from one eye at the time, infants show well-developed OKN from birth. OKN is quite important in its complex relationship with vestibular stabilisation. VOR is that system that maintains the eye's gaze direction in spite of head rotation. VOR and OKN compensate for head changes: the VOR gives the initial ocular stabilisation, the OKN adds any necessary duration components. Both systems compensate better image sliding generated by head rotation or body movement in space. The VOR is also important in the maintenance of posture during body movement. The VOR achieves adult level over the first 5–6 years.

It is rather evident that the visual mechanism is a complex neural network. The visual system intervening on the perception of objects, i.e., ventral system, is considered to be separate from the visual system intervening on the location and action directed at the perceived objects, i.e., dorsal system. Both systems come into existence with information contained in the pattern of activity in the cells of the retina caused by the light that occurs in that part of the eye. The ventral perceptual system projects from V1 through a set of cortico-cortical projections such as ventral temporal and occipital structures to anterior temporal cortex, i.e., the inferotemporal cortex. This system affords detailed representations of the world needed for cognitive operations like recognition and identification. The dorsal action system projects from V1 to posterior parietal structures affords an adaptable control of subcortical visuomotor areas. The dorsal system provides representations of the localised objects in the visual space (Fig. 2). Even if we put greater emphasis on differences of the ventral perceptual and dorsal action systems, both systems process information about object characteristics, such as size, orientation, shape, and shadow and both dispose information of spatial location. Transformations accomplished in the ventral system authorise the formation of perceptual and cognitive representations that enclose the continuing ingredients of objects and their spatial relations with each other. Transformations achieved in the dorsal system utilise instantaneous object characteristics that are constructed within egocentric format of reference to mediate representations related to the control of goal-directed actions.

The developmental trajectory of the two systems provides developmental erratic results. Studies comparing directly the developmental stages of both visual systems have revealed that functions mediated by the ventral system mature earlier than those mediated by the dorsal system (e.g., [100]). Young infants appear capable to perform any actions that are regulated by perceptual information (e.g., [22]). The developmental stage at which the specialisation of both systems becomes similar to adult have given uncertain findings. Some studies claimed that even if the two different neural systems are developing within the first year of life (e.g., [80]), both systems become specialised to treat different aspects of the same object as early as 5 years of age even at the very basic level of visual coding (e.g., [8]).

Indeed, many visual capabilities such as perception of colors, depth, and perception of motion start to develop soon after birth and continue to mature as infants experience the world around them. Using functional magnetic resonance imaging (fMRI) to record brain activity in awake 7-week-old, Biagi et al. [20] revealed early maturation of the cortical areas including MT+, V6 as well as the vestibular cortical area PIVC/PIC for motion process. The comparison with adult's brain activity gave

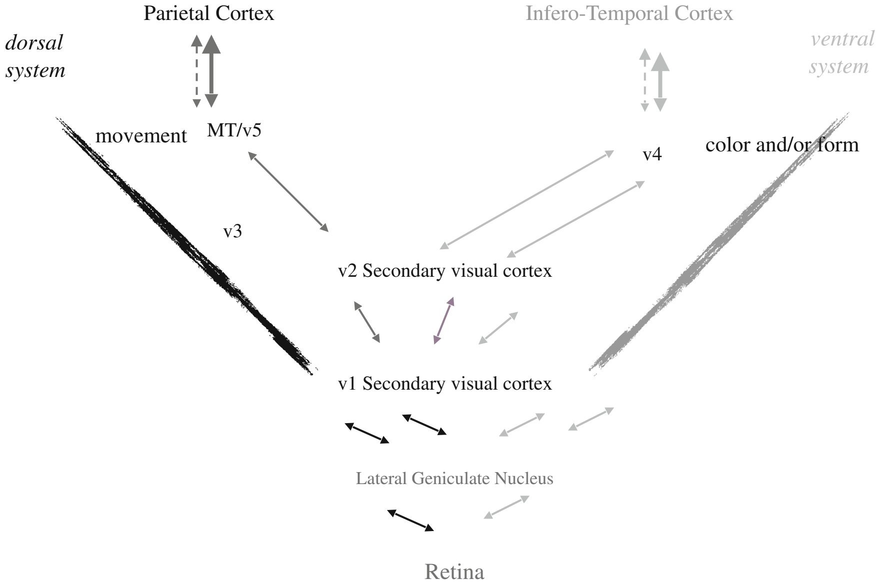


Fig. 2 From retina to dorsal and ventral systems

several similarities of MT+ areas both in the left and the right hemispheres and differences in V1 area as well as in PIVC/PIC area.

Briefly, infants come in the world with a neural system to see and perceive what is around them, but their visual structure is poor, the most primary functions are immature. Their visual development is characterised by critical periods in many notable visual functions, and by extensive learning from experience and increasing control over the visual mechanisms. Ventral and dorsal systems authorise infants to transform visual information into cognitive representations associated with object's recognition and location in the egocentric space all along static and dynamic motion activities. Visual areas serving dynamic motion process allow infants to harmonise visual motion with vestibular information to discern their own body position and movement in space.

3 Peripheral and Central Vestibular Organisation

The vestibular system, or labyrinth, is one of the most ancient sensory system. It consists of sense organs in the cavities of the inner ear. It allows vertebrates identify and adjust the position of their body and their movement in space.

Using scanning electron microscopy vestibular receptors were well identified. At 8 weeks all receptors were individualised and differentiated. Conversions in cristae shapes take place in rapid steps with a pause in the maturation process between the

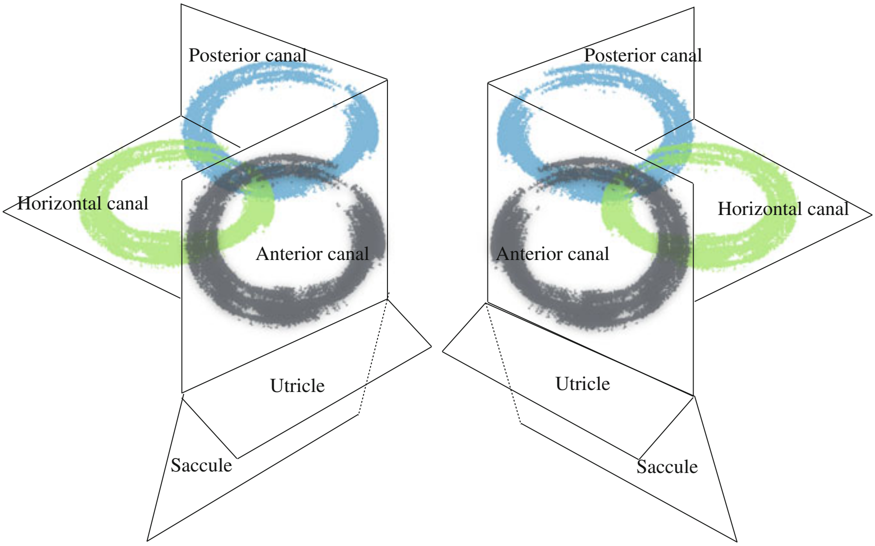
9th and 12th weeks. The utricles develop earlier than the cristae. Indeed at 14 weeks, all the receptors had an adult profile with the exception of cristea, which have only approached 55% of their adult size (e.g., [35]). The peripheral vestibular apparatus develops earlier than the central nervous apparatus.

The peripheral apparatus is composed by the semicircular canals and the otoliths organs. Both are completely similar to all the vertebrate phyla. Many studies have differentiated between static or head position receptors, i.e., the otoliths organs and dynamic or head movement receptors, i.e., the semicircular canals. The semicircular canals report the magnitude and direction of angular motion, however it is produced, the otoliths report the magnitude and the direction of linear motion (e.g., [106]). Both organs are therefore dynamic and static receptors. It is generally accepted that angular acceleration will have some effect on the utricles and linear acceleration will have some effect in angular acceleration. There are anatomical arrangements of the semicircular canals and cochlea that are suspended in the perilymph. Inside, the organs share a common cavity filled with the endolymph.

Labyrinthine semicircular exteroceptors share a common cavity in the utricule-canal system with the saccule and the saccule with the cochlea (e.g., [70]). There are three types of canals: the horizontal, the anterior vertical, and posterior vertical (Fig. 3a). When a person holds the head in a natural posture, the horizontal canals are almost parallel to the earth-horizontal plane. When the head is in a natural position the posterior canal lies in an almost vertical plane which forms an angle of 45° to the frontal plane of the head and the anterior canal lies in a plane inclined at an angle of about 15° to the vertical which also forms an angle of 45° to the frontal plane. Each of the three canals has a contralateral pair that forms a functional unity, a synergistic pair. In that context, the two horizontal canals, the left anterior and the right posterior canals and the left posterior and the right anterior canals form synergistic pairs. Following the hydrodynamic theory of the canals, the movements of the endolymph are important in order to analyse the angular motion. The microstructure of the sensory epithelium of the cristae comprises two types of sensory hair cell: type I and type II. Type I cells are enclosed in a goblet-shaped nerve chalice innervated predominantly by the larger diameter fibers in the cristal nerve. They are excited by ipsilateral acceleration. Type II cells are cylindrical and innervated by small diameter nerve fibers. They are excited by contralateral acceleration. Both types of cells are also innervated by efferent neurones. Each sensory cell is composed by sterocilia and one kinocilium. The increment of the resting discharge is produced during depolarisation, i.e., the inclination of the sterocilia is in the direction of the kinocilium, the decrement during hyperpolarisation, i.e., the inclination of the sterocilia is in the opposite direction of the kinocilium (Fig. 3b).

Labyrinthine otolithes exteroceptors, i.e., utricule and saccule are cavities at the junction of the three semicircular canals. Each cavity is filled with endolymph and contains a sensory epithelium, the macula, which responds to the magnitude and direction of linear acceleration. Their mode of functioning is remarkably constant. The utricular macula is relatively in the same plane as the horizontal canal even through it twists upwards at its anterior end. The saccular macula lies on the medal

(a) Otoliths and semicircular canals



(b) Hydrodynamic theory of the canals

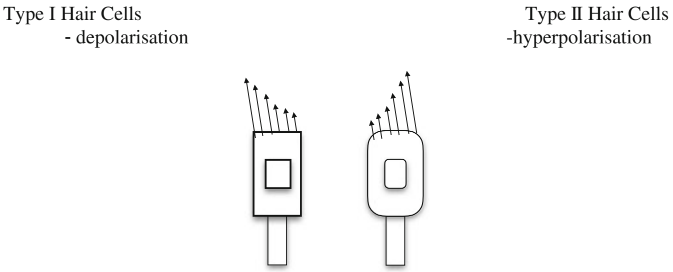


Fig. 3 Functions of vestibular organisation (**a** and **b**)

wall and is tilted inwards from the vertical by at least 20°. The outer part of each macula is concave. The cellular structure of the macula is composed by 33,000 hair cells in the utricule and 19,000 in the saccule. Each cell has about 70 stereocilia and one kinocilium. The membrane potential is maximally depolarised when a force shares the stereocilia in the direction of kinocilium, i.e., increases the resting discharge rate and is hyperpolarised when a force acts in the opposite direction, i.e., decreases the resting discharge. The geometry of the otolith organs is complex. Indeed, utricular macula and saccular macula are a multidirectional detector with several outputs, each of which increases or decreases according to the linear vector along its polarisation axis.

The influence of angular and linear accelerations expands all over the central nervous system to involve brain functions related to visual perception, somatosensation, movement, and memory. A possible consequence of that is the fact that the physiological activity of vestibular apparatus influences the activity of central as well as peripheral nervous system (e.g., [70]). Indeed, the peripheral vestibular system provides the central vestibular system with information concerning the movement of the body and its position in space.

The central system uses this information along with visual and somesthetic information to create the associated representations. The central vestibular system path involves the vestibular nerve projections from the peripheral vestibular organs to the vestibular nucleus in the brainstem but also the projections from the brainstem to cerebellum and finally the cord spinal and thalamic nuclei and from the thalamus to the cerebral cortex (e.g., [137]). A lot of neuroimaging studies specially those used functional magnetic resonance imagery (fMRI) were utilised to analyse vestibular processing in humans. Using specific head postures, it has been revealed that peripheral vestibular stimulation causes activations within the thalamus via the vestibular nuclei (e.g., [82]). There is some evidence that vestibulothalamic circuits would form specialised tracks that incorporate vestibular signals with other modality-specific information within the thalamus (e.g., [95]). Ventrobasal nuclei receive vestibular projections from bilateral superior vestibular nucleus but also contralateral medial vestibular nucleus via the medial longitudinal fascicles (e.g., [98]). Ventral posteromedial neurons simulated linear and circular movements (e.g., [97]). All these nuclei project to vestibular cortical regions as anterior suprasylvian cortex, and the intraparietal sulcus (e.g., [26]). In addition, Deecke et al. [37] have reported evidence that some posterior thalamic nuclei are also activated during somesthetic cutaneous stimulation. They project directly to primary somesthetic cortex, to secondary association somesthetic cortex (e.g., [36]) as well as to posterior parietal cortex (e.g., [99]). Moreover, the ventral anterior and lateral nuclei project to primary motor and premotor cortices, i.e., 4 and 6 Brodmann's areas respectively (e.g., [137]). A meta-analysis on 16 studies has reported that different cortical areas such as Sylvian fissure, insula, retroinsular cortex, frontoparietal operculum, superior temporal gyrus as well as the cingulate cortex are associated with the vestibular cortex (e.g., [96]).

Associated with cortical and subcortical functioning, the anatomical organisation of the vestibular system is rather bilateral than unilateral (e.g., [25]). The central vestibular system joins together ipsilateral and contralateral sensory tracks from the vestibular nuclei to the midbrain tegmentum, the thalamus, and the cortex. Another part of the system is the hippocampus and the parahippocampus where vestibular information is processed.

In sum, the vestibular system matures early. It is represented by the labyrinth of the inner ear bilaterally in most mammals. To analyse rotational and translational movements, the vestibular system is structurally composed by the semicircular canal system, which displays angular accelerations; and the otoliths, which display linear accelerations. The vestibular system sends signals primarily to the neural structures that command eye movements, i.e., vestibulo–ocular reflex, which is required for clear vision, and to the muscles, i.e., proprioceptive system, that command posture, which is necessary to keep infants upright. Together with the visual and somesthetic information, bilateral vestibular organisation not only contributes to the equilibrioception in three axis (sagittal, vertical, and lateral) at subcortical level, but it is directly and indirectly involved in internal representation of the body, navigation, memory and orientation at cortical level.

4 Internal Representation of the Body

To perceive our own orientation in space, the brain needs to compute and continuously update spatial information which is the base of the internal representation of the body. This internal representation is a dynamic process, enabling conscious and unconscious perception. Dynamic in nature, the vestibular system is crucial (e.g., [4]). The existence of two interdependent somesthetic graviceptive systems in humans has been established, aside from the otoliths of the vestibular system: the vascular graviceptive system, and the kidneys (truncal graviceptive system) (e.g., [101]).

The internal representation and orientation of the body in space have been amply studied in humans. Experiments have been carried out through apparent postural vertical or apparent upright (e.g., [13]) on the roll or sagittal *X*-axis. Postural vertical was most often studied with this roll or sagittal *X*-axis, although some experiments were also reported about postural vertical with the pitch or vertical *Y*-axis (e.g., [21]). Postural horizontal has less often been examined with the sagittal *X*-axis (e.g., [59]) and with the *Y*-axis (e.g., [79]). Only one study has compared the internal representations of the body via a task of self-controlled whole-body orienting about roll (*X*-axis) and pitch (*Y*-axis) rotation axes (e.g., [50, 76]) (Fig. 4).

In that study, participants were seated on a rotating chair. They were required to position themselves horizontally (=90°) from a different initial tilt of body, in complete darkness, and thereafter vertically (=0°). The accuracy of body orientation was measured and compared between both directions for *X*- and *Y*-axes. It was expected that the internal representation of body orientation would be different between these two axes, mainly because of the seated posture (often no experience of seated roll rotations) of the participants. It has been shown that the internal representation of body orientation is different according to these two rotation axes. It seems that there was a systematic and symmetrical difference between the prone and supine sides on the *Y*-axis. More precisely, the participants turned too much on the prone side (ca. 11°), and not enough on the supine side (also about 11°), when trying to align along the earth-horizontal on this pitch-axis. In the contrary, there was no side effect on the *X*-axis (Fig. 5). This seems to confirm a basic difference between both axes, which relies most probably on the internal representation of body orientation.

Guedry [59] described a strong effect of reduced somesthetic cues on subjective postural horizontal and vertical. Indeed, with studies during water immersion, it had been suggested that the utricles do not provide good static indication of orientation (e.g., [79]). It was also noted that 10° up or down from horizontal seems to be a

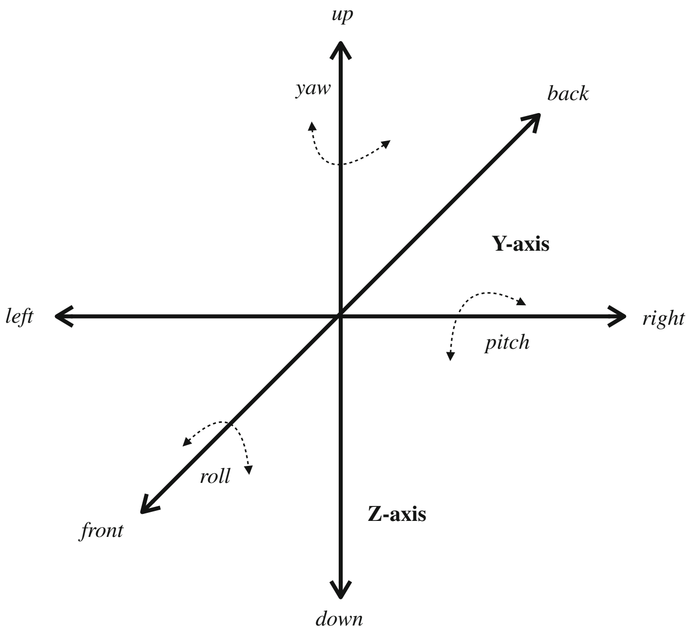


Fig. 4 Three axes of the body (*X*-sagittal, *Z*-vertical, *Y*-lateral)

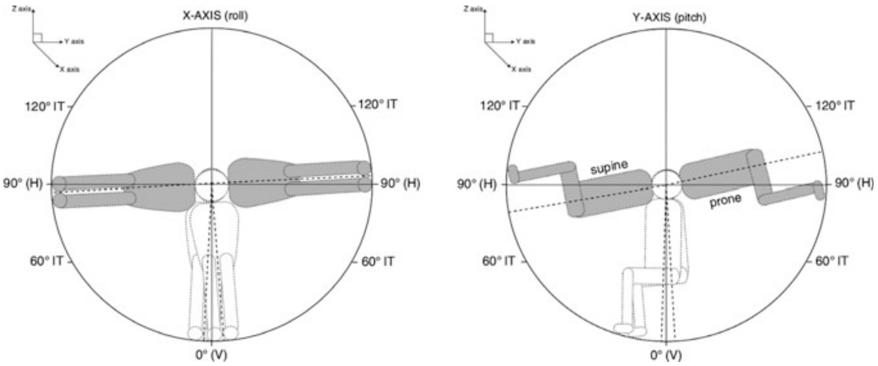


Fig. 5 Subjective horizontal and vertical on the *X*-axis and *Y*-axis (from [76])

range within which the otoliths are relatively insensitive in signaling head orientation relative to the gravitational force vector (e.g., [86]). When participants attempted to set themselves to the upright through *X*-axis when seated on a chair, all reported using pressure cues (e.g., [65]). A dominance of proprioceptive input over vestibular input has been shown through differential rotation of the feet and/or the trunk about the vertical *Z*-axis (e.g., [67]). The authors concluded that, perceptually, the vestibular information is linked to the foot support body representation through proprioception. They further suggested that body position perception is built bottom-up with the feet related to space coordinates (vestibularly derived), the trunk related to the feet and the head to the trunk. Perception would use vestibular input to control for stationarity of external references and if true, would rely on these instead of the vestibular derived space reference. It had been also suggested that sensory information from vestibular system and from somesthetic afferents in feet and ankles play an important role in determining the availability of postural strategies (e.g., [86]). The influence of touch and pressure cues on apparent orientation during "barbecue" rotation has clearly been demonstrated (e.g., [129]).

In the study presented above, (e.g., [76]) participants were firmly embedded in deflated pillows, so that somesthetic cues, i.e., touch and pressure cues, were reduced. The forward tilted posture that has been observed represents probably a kind of "default" reaction to keep balance in critical situations. It is probably due to the proprioceptive backward-tilted referential of verticality (e.g., [10]). Furthermore, Barra et al. [12] revealed the existence of a synthesis of vestibular and somaesthetic graviception for which the posterolateral thalamus plays a major role, corresponding to a primary property of internal models and yielding the neural bases of the Aubert effect. They concluded that humans construct and update internal models of verticality in which somesthetic information plays an important role. The participants behaved as if they could "see the vertical". Subjective postural horizontal and vertical rely on mental imagery and on the internal computation of an head-foot line, both involving an internal representational system (e.g., [109]), i.e., an internal body representation providing a basis for conscious and unconscious perception.

With the *Y*-axis, subjective horizontal was about 11° too high or too low. Consider a subject with 80 cm ear-hip and 50 cm knee-feet length, and with 30 cm hip-knee. The angle of the ear-feet line would then be arctan (30/130) = 13°, rather close from the 11° found. This suggests that participants adjusted the orientation not of their trunk, but of a "virtual line" joining head and feet. This "virtual line" materialises the internal representation of the body. It is based on vestibular, somesthetic, and vascular graviceptive afferents. When reaching subjective vertical, whereas this head-foot line assumption does not strictly hold anymore, participants still seemed to be attracted toward it on the forward direction and front side. The trunk axis weight is probably increased due to its real weight, now parallel to the gravity vector.

In other words, the internal representation of the body is related to the internal representation of the verticality. The participants behaved as if they could "see the vertical", from supine, and therefore they stopped rotating right on it. Rotation not only "reorients" the canal and otolith information relative to gravity but also transforms somesthetic graviception. Both receptors seem to be interdependent in order to lead to a robust judgement of vertical postural sense. These behavioral findings seem to be coherent with neurophysiological data showing that vestibular, somesthetic graviceptive afferents and the Bayesian probability theory established that the perception of ego motion direction relies on integration of multiple sensory cues. All these afferents which are interconnected in cortical and subcortical levels [26] are transformed into representations that contribute to the internal representation of the body. The internal representation of the body can be thought as an egocentric reference providing spatial representation and orientation.

5 Spatial Representation

As explained previously, in the brain not only visual but also multiple vestibular and somesthetic information is crucial for the performance of navigation. One of the indicators of spatial behavior is the capability to pursue a moving spot with hand and eye movements. Such an ability supports visual and vestibular anticipation, at least. It appears early in development. It seems that infants aged 6 and 14 weeks are able to discriminate between motion directions and pursue small visual objects (e.g., [113]). Even better, neonates as young as 3-days old seem to be able to display visual, vestibular, and proprioceptive responses through head movements when exposed to visual stimulation (e.g., [123]). Infants seem also to be able to continuously produce smooth pursuit eye movement at 2 months old (e.g., [135]) and discriminate between different kind of visual motion, i.e., real or virtual, at 3 and 5 months old (e.g., [53]). Jonsson and von Hofsten [81] have demonstrated that at 6 months of age healthy infants can produce predictive head and eye movements and anticipate the final position of a visual object.

Using EEG in 8-month-old infants and adults, studies have reported that these is a difference in brain activities related to the processing of optokinetic information. Infants have shown longer latencies than adults for random visual motion (e.g., [130]). No walking infants aged 4–5 and 8–10 months detect visual motion less efficiently compared to adults (e.g., [131]). Older infants seem have a more developed neurobiological system that permits them to use the vision motion information like adults. It is well documented that the cortical and subcortical areas related to visual motion perception continue to develop through infancy to adulthood (e.g., [54]). The more efficient processing of motion is related to the old than to the young infants. Locomotion experience influences changes in brain activity and vice versa (e.g., [92]). Agyei et al. [2] investigated the effect of visual motion perception in prelocomotor infants aged 3–4 months and locomotor infants aged 11–12 months. Only locomotor infants have rapid and compatible reactions with forward visual motion information. Furthermore, crawling experience is relevant (e.g., [3]).

Anticipatory and compensatory postural activities have been found to be associated to visual mobile information in infants between 10 and 17 months (e.g.,

[88]). Such activity is progressively developed with age as infants learn to stand and walk (e.g., [118]). It helps them to keep balance during locomotion. Cignetti et al. [33] have reported that the acquisition of locomotion enhances sensorimotor control of posture. Peripheral visual information is more effective and goes hand in hand with balance and self-locomotor experiences in typical children (e.g., [130]).

The balance structure authorises children to keep up equilibrium by incorporating internal and external information during static and dynamic situations. Balance development starts with the maintenance of balance. Being able to remain upright allows children for touching, grasping, and reaching. The method of "swinging room" developed by [91] has been widely used to investigate the stability responses of infants and children. Follow the principle, children stand in a platform surrounding by a room. The walls and the ceiling of the room move back and forth independently of the floor that is fixed. This movement provokes children to sway with the direction of the room. Forward movements of the room cause backward movement to the children that is thought to be a way to compensate the loss of balance.

Sway responses seem to be present very early in life. At 5 months of age, infants sway in synchrony with the room when sitting (e.g., [19]). The degree of sway is high for infants with crawling or self-locomotion experience only (e.g., [64]). New locomotors can bumble or fall over. The same behavior is also observed on children aged 3–4 years old (e.g., [134]). The influence of visual information to balance decreases between 4 and 6 years old (e.g., [55]). It seems that the gain of sway when submitted to a visual information produced by a swinging room is higher in children aged 7–14 years than in adults (e.g., [125]). Children body sway reaches adult level by 10 years of age (e.g., [112]). When vestibular and proprioceptive information are considered only, significant sway responses are observed in healthy children older than 4 years. Haptic (e.g., [11]) as well as proprioceptive sources of information are sufficient to induce sway (e.g., [124]). It seems that children aged 4–6 years old are more destabilised than adults during sensory conflict: proprioceptive system signifies no movement but vision or vestibular system signifies movement. In other words, the aforementioned studies suggest an early reliance on visual information. It appears that the end of this period and transition emerges around 5 years (e.g., [107]).

In sum, in active or passive locomotion a large range of sensory information can potentially provide feedback including visual, vestibular, and somesthetic (proprioceptive and haptic) inputs. Balance and locomotion are highly interdependent: balance authorises children to walk safely, locomotion improves the control of balance. Balance and locomotion provide the ground of spatial navigation toward objects and locations. Visuomotor, vestibular, and somesthetic abilities give children and adults the possibility to explore actively or passively the space. Cognitive factors influence ego motion in children and in adults.

6 Linear Sagittal Ego-Motion Perception

Ego motion is described as an embodied sensation of movement in space than can be experienced by an observer when s/he is submitted to appropriate visual inputs (e.g., [51]). Similar movements can be induced by other sensory inputs such as auditory, tactile information, and muscular proprioception (e.g., [85]). Ego motion can be global, i.e., involving the whole body, or segmentary, i.e., involving some parts of the body (e.g., [127]). Global ego motion is described with respect to the three mutually orthogonal axes of an upright observer: the sagittal *X*-axis, the lateral *Y*-axis, and the vertical *Z*-axis. Ego motion rotation around one of these axes is named roll (around the *X*-axis), pitch (around the *Y*-axis), and yaw (around the *Z*-axis). Accordingly, ego motion translation along one of these axes are labeled sagittal, lateral, and vertical (along the *X*-axis, *Y*-axis, and *Z*-axis respectively).

Studies on ego motion have been conducted from various standpoints. However, during the past two decades, a growing tendency has emerged for such motion to be studied less and less as a basic sensory process and more and more as a complex integrated perception (e.g., [114]). Only marginal attention has been paid to the possible involvement of cognition in ego motion. Various data allow one to consider contradictory hypotheses.

From one hand it is suggested that ego motion is independent of cognition. Several examples support this position. Stationary observers bilaterally exposed to a backward sagittal visual scene, experimental or naturalistic, experience ego motion even if they are facing a physical obstacle, i.e., a wall. This means that the observer's knowledge of a physical obstacle to a real forward body displacement does not prevent the onset of a forward ego motion (e.g., [23]). Analogously, the segmentary extension of lesion or the forearm either vibratory (e.g., [56]) or visually induced (e.g., [127]), has been felt even when the observer know that their forearm is restrained or physically immobilised by an arm holder. The above data suggest that ego motion is independent of cognition.

From the other hand some data lead us to hypothesise that ego motion might be subject to cognitive modulation. In some studies it appears that the same information that can induce ego motion may be modulated or differentially interpreted according to the context. Young and Shelhamer [143] exposed adults to a dome rotating around the *X* axis of the head. In one condition, called "free-floating", the observer was only restrained by a custom-fit bite board. In the other, named "tactile", the observer restrained by the bite board was also held on the floor surface by a stretcher elastic from a shoulder harness. The observers have reported much stronger ego motion in the "free-floating" than in the "tactile" condition. The interpretation of such a situation is strongly attached to the existence of cognitive factors associated to a specific knowledge of body orientation. In Baumberger's study [15], children aged 8, 10, and 12 years old and adults had to aim at the memorised location of a stationary target in either a mobile or an immobile visual environment. In all population aiming was much more imprecise in the visually mobile environment than in immobile one. Moreover, when aiming was under the visually mobile condition, the aiming errors were more important in children than in adults and more important in 8 years than in 12 years of age. The errors were attributed to the ego motion in all the groups. All the errors were quite remarkable as all the participants have aimed as if they have really changed their body position in space along the sagittal axis, i.e., *X* axis.

Direct cognitive effects on linear forward sagittal ego motion in children have been investigated when they were exposed to a visual experimental scene [89]. Children aged 7 and 11 years old were in the same physical position, i.e., seated in a stationary armchair, but in two contrasted cognitive conditions. In one condition, the children were informed that the stationary armchair could move, in the other that it could not move. Even if the probability to obtaining ego motion it was not affected by the knowledge about the possibility of a physical displacement, the results have shown that ego motion was more rapidly obtained when the displacement was known to be possible than when it was know to be impossible (Fig. 6). Everything happened as if the cognitive preparation has changed the observer's response criterion. It seems that the cognitive preparation have had some top-down effect on the sensory integration sites, where visual information is processed as specifying body movement. The absence of effects on ego motion occurrence and the presence of an effect on timing for reported ego motion can theoretically be accounted for in the context of visuo-vestibular interaction.

Based on the above study, Shirai et al. [122] have studied the development of linear ego motion by comparing children aged 9 and 14 years old with adults aged 21 and 22 years old. Considering the sensory level only, their results are consistent with the fact that children are more sensitive to ego motion than adults suggesting that there is a difference in the level of perceptual engagement between both groups.

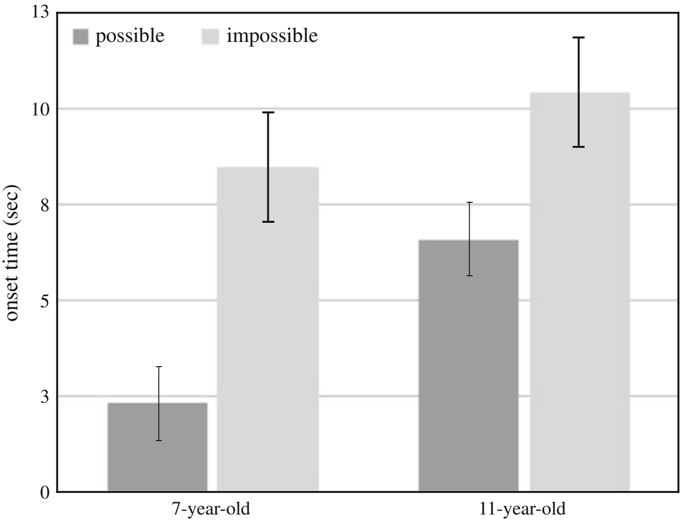


Fig. 6 Median self-motion onset time for each cognitive condition within each age group

Similar findings have observed in children aged 7 years old (e.g., [14]). In that context, linear forward ego motion behavior is thought to be associated to children's immature capability to use vestibular and/or somesthetic inputs, i.e., non-visual, to treat ego motion (e.g., [121]).

Linear forward sagittal ego motion has been also analysed in healthy adults aged 26 years old via visual strategies. The aim of the study was to compare visuomotor and attentional strategies of individuals when exposed to two naturalistic visual environments: a real traffic urban scenario prerecorded on video; and a virtual scenario, i.e., the 3D simulation of the same scene that represents a district of the center of Paris, between the Louvre and the Opera (e.g., [49]) (Fig. 7). Participants' eye movements (amplitude and latency) and fixations (number and time) were recorded using a binocular eye tracking system (Eyelink II). The number of fixations was higher in the prerecorded than in 3D simulated environment, which would mirror participants' need to renew their perception. This latter behavior is a classic one in real situations (e.g., [52]). Analogously, the fixation time was higher in the prerecorded environment than in virtual one explaining a more attentional engagement in the former environment than in the recent one. Saccades' amplitude and latency were more important in the prerecorded than in the virtual environment. It is well known that eye movements are strongly linked to visual attention: the more eye movement the more the attention (e.g., [66]). As the prerecorded environment is richer in visuospatial information than the virtual one, making more fixations and saccades implies higher neurocognitive functions. In other words, the exposition of participants to a prerecorded environment would necessitate more cerebral activity than to the virtual environment. This is also corroborated with the declaration of participants "prerecorded environment are more rich than virtual environments." Information recall is a genuine memory process, which constrains retention in visuospatial working memory. Different explanations, such as integration in saccade memory buffer or the fact that perception is renewed with each

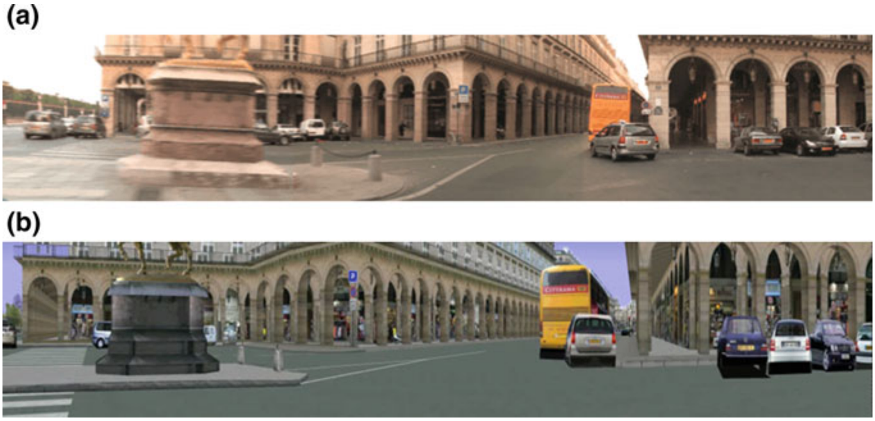


Fig. 7 Naturalistic prerecorded (**a**) and virtual (**b**) environments: Louvre-Rivoli base (from [50])

fixation and saccades are coherent with that. Neuroimaging data also suggest the presence of common cortical areas for attention and memory processes (e.g., [117]).

A more recent study has investigated the cognitive and physiological processes associated with forward sagittal ego motion and spatial intuition in healthy adults 20 years old (e.g., [45]). An experimental group and a control group have been considered. All the participants of the experimental group were immersed in the virtual naturalist environment after having been immersed in a real one containing visual and olfactory information correlated with the experimental task: name a preselected place in the naturalistic environment. All the participants of the control group have been immersed in the virtual environment after having been immersed in a neutral real environment. Somesthetic electrodermal activity and verbal declaration have been recorded. The median electrodermal activity as well as the coefficient of variation of the electrodermal activity were more important for the experimental group than for the control group. In addition, the comparable configuration of results is observed for the verbal declaration between both groups. A continuity between somesthetic and cognitive factors would be on the basis of spatial intuition in ego motion. In other words, in real and virtual environments although vision is the most characteristic, other information are significant: vestibular, and somesthetic. In the following part, the visuo-vestibular and somesthetic contribution to ego motion will be analysed in sagittal as well as in vertical ego motion condition.

7 Linear Sagittal and Vertical Ego Motion Perception

Linear and circular ego motion perception is a visuo-vestibular phenomenon basically (e.g., [136]). The visually induced ego motion is characterised by three main perceptual phases. At the beginning of the visual motion (peripheral or central), an observer perceives her/himself as stationary and the visual environment as mobile. In a second phase, the observer begins to perceive the mobile visual environment as moving more slowly and her/himself as gradually moving in the opposite direction. Finally, in a third phase, the participant receives ego motion only and the visual environment looks stationary (e.g., [51]). The transition from a perceived self-stationarity to a perceived ego motion is theoretically framed as resulting from a conflictual interaction between the visual and the vestibular system (e.g., [40]). Naturally, for an observer exposed to a mobile scene, the vestibular inputs indicate self-stationarity while visual inputs indicate ego motion. In their model, Zacharias and Young [144] posed that the conflict is the difference between two signals: one vestibular and one visual. The vestibular signal indicates self-stationarity on the basis of the resting activity of the vestibular system (e.g., [18]). The other is a visually generated reference signal. This latter is assumed to be the vestibular signal, which would be expected if the visual movement was due to a veridical movement of the observer in space. When suddenly exposed to a constant velocity visual scene, a stationary observer is in the middle of a conflict at the movement start and this conflict disappears later on as the constant-speed visual mobile scene continues. Since the reference signal is supposed to correctly represent the vestibular dynamics associated to Zacharias and Young's model, different characteristics of ego motion should be related to vestibular sensitivity (e.g., [68]).

Converging neuroanatomical studies carried out that various cortical areas are specialised in visuo-vestibular afferents in humans associating frontal, temporal, parietal, and prefrontal cortex (e.g., [24]). Some others have shown that the temporoparietal cortex would selectively be involved in the treatment of visual and vestibular interaction. Vestibular projection area is rather associated with the neural activity of the occipito-temporo-parietal cortex (e.g., [16]) and is involved in the complex representations of egocentric perception of the body in space in both static and dynamic conditions (e.g., [47]).

Several characteristics of ego motion have been found to depend on the magnitude of conflict between visual and vestibular inputs. It has been shown that pitch ego motion is generally accompanied by a limited tilt of the body in vestibular-healthy observers on earth (e.g., [71]). The body tilting is thought to be due to the conflict between visual information, vestibular otolith information and somesthetic receptors (e.g., [41]). It increases markedly when the vestibular afferents are reduced by lateral head tilting in healthy observers on earth (e.g., [142]) or suppression of graviceptive information in weightlessness (e.g., [30]). Patients with bilateral labyrinthine defects may experience not limited tilt but complete body rotation (e.g., [31]). Similarly, the feeling of ego motion is asymmetrical in patients with unilateral Manière's disease while it is symmetrical in healthy observers (e.g., [139]). In addition, in vestibular-healthy participants, ego motion is more important in weightlessness than on earth (e.g., [143]). The aforementioned data suggest that the provoked decrease in vestibular inputs in weightlessness or the invoked decrease in vestibular sensitivity in vestibular patients would both have facilitating effects on ego motion because of the reduction in the visual–vestibular interaction (e.g., [47]). In other words, ego motion seems to be facilitated by the reduction of visuo-vestibular conflict.

Physiological data suggest that typical human vestibular sensitivity varies between sagittal and vertical axes. As analysed previously (cf. peripheral and central vestibular systems), the otolithic system is functionally adapted to transduce the magnitude and direction of linear acceleration (e.g., [17]). It comprises the utricule and saccule that transduce horizontal accelerations and vertical accelerations respectively. Studies have shown that utricule has a greater sensitivity than the saccule in normally positioned head (e.g., [128]). With that in mind, it is possible that the visuo-–vestibular interaction differs between sagittal and vertical axes. Sagittal ego motion is less easier to be induced than the vertical ego motion in healthy observer (e.g., [47]).

The results suggest that the normal intra-individual variation of the human vestibular sensitivity between head axes could account for the normal variation of the ego motion between head axes [e.g., 47]. This would signify that the normal variation of human vestibular sensitivity in the terrestrial environment would modulate the magnitude of the visual–vestibular interaction and ego motion. A research has attempted to expand this rationale to the inter-individual level. Both vestibular and ego motion sensitivities are known to be inter-individually variable among healthy participants. In that context, vestibular and ego motion sensitivities are negatively correlated: the lower the vestibular sensitivity, the higher the ego motion sensitivity. This correlation may have two meanings. On the one hand, it may be that ego motion and vestibular sensitivities are intrinsically related. This would suggest that ego motion sensitivity would be only partly determined by the reference signal as originally conceived by Zacharias and Young [144]. On the other hand, this would suggest that, although ego motion and vestibular sensitivities are intrinsically related also depended on other kinds of information such as somesthetic afferents (e.g., [90]).

En masse, linear sagittal ego motion of the body seems to be determined by cognitive and vestibular components. The intra-individual variability of vestibular sensitivity between sagittal and vertical axes would explain the intra-individual variability of the ego motion sensitivity between both axes. The inter-individual variability of vestibular sensitivity along the vertical axis would explain the inter-individual variability of the ego motion sensitivity along this axis. In addition, exclusively cognitive variables such as the representation of the plausibility or implausibility of the ego motion is capable of modulating the ego motion sensitivity. Visual attentional factors and memory process specially those associated with visuospatial working memory can be considered as decisive elements of ego motion of the body in real and virtual environments. The following point will analyse the relationship between ego motion and the associated somesthetic cardiovascular activity.

8 Somesthetic Inputs to Linear Vertical Ego Motion Perception

Vertical ego motion perception, i.e., elevator movement, can occur in naturalistic situation when, for example, we take a glass-walled elevator to move upward or downward. Though a rapid waterfall is seeable (frequently present in international airports, centers and buildings), we can have the impression that our elevator is moving at the opposite direction (downward or upward). This visually induced ego motion perception is a complex phenomenon which necessitates bimodal visuo-vestibular interaction at least (e.g., [48]). Studies suggest that there is a differential sensitivity between utricular maculae (transduces horizontal accelerations) and saccular maculae (transduces vertical accelerations) in the otolithic system of healthy observers (e.g., [69]). Moreover, when saccular maculae are maximally aligned with gravitational force, electrophysiological and psychophysical findings have reported a differential sensitivity to opposite accelerations within the vertical axis (e.g., [46]). Downward ego motion is more easily induced than upward movement especially because of the same direction with gravitational acceleration (e.g., [51]).

It has been shown that in healthy participants with erect head aligned in the vertical axis, the otolithic saccular acceleration regulates the heart rate thanks to the activation of the autonomic nervous system [e.g., 140]. Precisely, otolithic stimulation leads to lower cardiovascular responses (i.e., low heart rate) in patients with bilateral labyrinthine disease than in healthy persons (e.g., [111]). Cardiovascular responses would be "vestibuloform" by the fact that they are produced only during activation of otolith receptors (saccular and utricular maculaes). In that context, the intensity of the visual–vestibular interaction that modifies ego motion perception would also modify the functioning of the autonomic cardiovascular responses: the lesser the vestibular sensitivity, the lower the cardiovascular reaction. This hypothesis has been tested by the measuring of the variation of heart rate in healthy people when experienced vertical ego motion perception. Due to the fact that the otolithic saccular sensitivity for upward ego motion is higher than for downward motion (e.g., [38]), the cardiovascular reaction, i.e., heart rate would be lower for downward than for upward ego motion perception (Fig. 8).

Expressly, under normal terrestrial conditions, it was not only demonstrated that the autonomic cardiovascular response (i.e., the heart rate) is lower for the downward than for the upward ego motion, but that there is also a significant difference in cardiovascular activity between the rest condition and the upward condition. The cardiovascular activity is higher in upward ego motion condition than in rest condition. Namely, these results are consistent with the hypothesis claimed that the cardiovascular responses would be "vestibuloform" as they can be influenced by the otolithic saccular receptors. Experiments on animals and humans participants have demonstrated that inputs from vestibular otolith organs contribute to the control of heart rate during movement (e.g., [111]). It follows that the intensity of the

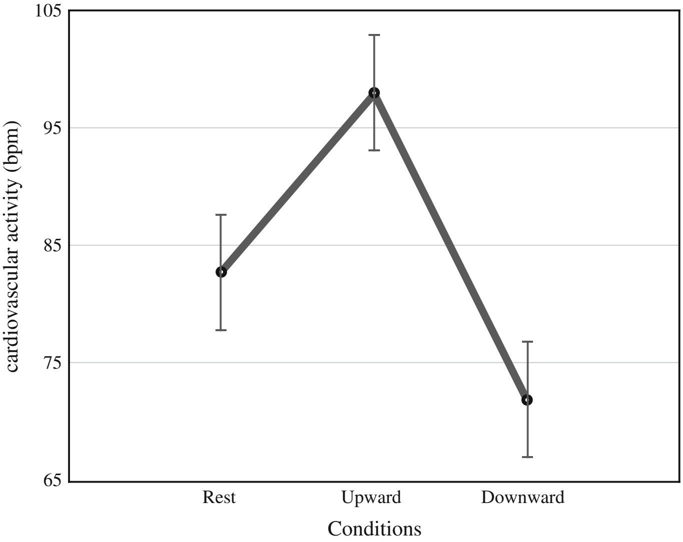


Fig. 8 Heart rate in vertical ego motion in space (from [51])

visuo-vestibular interaction along the vertical axis would also reshape cardiovascular activation depending on the directional condition (upward vs. downward). It is lower for downward ego motion that for upward ego motion. In other words, these data are clearly consistent with studies that have demonstrated that any reduction (because of the differential vestibular sensitivity) or loss of vestibular information, as it is the case in patients with unilateral or bilateral labyrinthine disease, provides an attenuation of the cardiovascular activation (e.g., [140]). Similarly, it has been established that the development of motion sickness that is characterised by increased ego motion perception leads to the disintegration of autonomic nervous system balance. And this is because, it is accompanied by an increase in sympathetic activity (and a decreased in parasympathetic activity). Analogously, the adaptation to motion sickness is accompanied by the recovery of autonomic nervous system balance (e.g., [72]). Significant changes in cardiorespiratory parameters occur during visually mediated illusory tilt and vertical ego motion. Such responses are consistent with the hypothesis that visuo-vestibular input contributes to the initial cardiovascular adjustment to a change in posture in humans (e.g., [73]). Even if, it is not possible to determine, with the present studies, the precise mechanism that occurs but rather can only speculate that it plays an obligatory role in producing changes in cardiovascular autonomic activation during otolithic engagement in healthy adults. These observations can be enriched by recent neuroimaging data underlying that the neural correlates of vertical ego motion perception (as linked to the gravitational field) activate a key cortex area receiving vestibular inputs: the PIVC parieto-insular vestibular cortex (e.g., [39]). This cortical area, which is directly and indirectly associated with the neural activity of the occipito-temporo-parietal cortex (e.g., [16]) and with the frontal, temporal, parietal, and prefrontal cortex (e.g., [24]) would also be associated with an internal model of gravity, i.e., an egocentric representation of the body in space that necessitates, as explained previously, the integration of visual, vestibular, and somesthetic information at least.

In sum, visuo-vestibular and somesthetic interaction together with cognitive factors strongly contributes to the ego motion. Both bottom-up and top-down processes act together in a synergic way to harmoniously perform spatial navigation.

9 Spatial Navigation in the Presence and Absence of Visual Afferent

In spatial navigation, humans can adopt two distinct strategies in order to take information about their position and orientation during travel: (1) navigation using landmarks from the environment and (2) path integration. It is this second ability that we use when we walk or are transported with our eyes closed (e.g., [105]). This kind of navigation involves two main parameters: perception of the distance and direction of movement. Updating these parameters is based on idiothetic information (e.g., [104]), arising from several sensory organs including the visual system, the vestibular system, the proprioceptive system (e.g., [102]). All information is integrated into an internal representation (e.g., [93]), which enables humans to navigate efficiently.

Through navigation based on idiothetic (i.e. internal) cues such as vestibular, proprioception, and visual (e.g., [103]), any human should continuously know his/her position with respect to the starting point (e.g., [105]). Accurate navigation from a start location to a goal depends on a constantly updated perception of one's location and direction of linear navigation, as well as the appropriate trajectory to reach the goal (e.g., [58]). Broadly, the perception of spatial linear navigation is multimodal, the experimental conditions but also the individual preferences such as cognitive mode seem to influence the selection of the relevant cue (visual, vestibular, proprioceptive) (e.g., [74]).

Continuous visual and vestibular signals interact in the brain. Visual sensitive neurons in the medial superior temporal area (e.g., [42]) and in the ventral intraparietal area (e.g., [27]) have visual receptive fields and are selective for visual patterns similar to those seen during ego motion (e.g., [87]). The neurons of both areas are also selective for motion in darkness, suggesting that they receive vestibular signals (e.g., [57]). The medial parietal cortex is assumed to provide spatial information tied to a specific view (e.g., [78]). This cortex is widely interconnected with higher cortical areas (including lateral PPC) and subcortical structures (e.g., [29]). A recent fMRI-study of spatial navigation found that the medial parietal cortex is the area in which activation increases during visually signaled forward navigation (e.g., [138]). The frontal lobes are special in that they have been associated with working visuospatial memory and planning, which all depend on the recognition and integration of a vast network of signals directly linked with spatial linear navigation (e.g., 116). Neuroimaging studies have also shown that somesthetic afferent signals reach the frontal and ventral prefrontal cortex also contribute to spatial navigation (e.g., [5]).

In the frame of spatial linear navigation, it has been revealed that during self-driven reproduction of passively traveled distances, the reproduced distances were longer in light than in darkness (e.g., [110]). Consistent with that are experimental observations following which the efficiency and accuracy of spatial navigation depends on the degree of lightness: both increase when lightness decreases (e.g., [28]). More specifically, visual information seems to cause an underperception of passive self linear navigation which leads to an overshoot of this navigation. This visual information effect seems to persevere during active movement (e.g., walking). Sun et al. [126] found that the availability of visual information during walking led to an underperception of movement (leading to overshoot) relative to conditions in which visual information was absent.

While the presence or the absence of visual information is analysed in the reproduction of passive/active movement, the importance of exteroceptive and proprioceptive somesthetic information on the reproduction of such movement is less documented.

Researchers have studied conditions in which visual information is removed and only proprioceptive (and vestibular) cues are available during active movement. Some results have clearly showed that participants were able to reproduce the imposed distance by walking without vision [94]. Some others have proved that individuals are able to estimate distance information when learning and responding through blindfolded walking (e.g., [44]). Without visual information, the effectiveness of vestibular information seems to be limited during larger scale navigation (e.g., [133]), when exteroceptive information such as vibrations is available (e.g., [119]). The mechanisms through which exteroceptive as well as proprioceptive information can be used to perform self-navigation have recently been studied. It has been suggested that humans use "step integration" to correctly realise self-navigation tasks (e.g., [43]). Step integration, i.e., path integration, might be reliable for short traveled distances (e.g., [32]). The aforementioned studies seem to inform us that at constant velocity, the availability of visual, vibratory and proprioceptive information influences the estimation and reproduction of spatial linear navigation.

Focalised on the way visual information could influence spatial linear navigation, a recent study had used a task of distance reproduction. Four distances (2, 4, 6, and 8 m) were used. The results of the study can be summarised as follows: (1) with visual information the reproduction of all distances was underperceived, i.e., participants overshot the distances to be reproduced; (2) without visual information the participants undershot the longer distances (Fig. 9). While with vision the reproduction seems more accurate than without vision, this was not always significant; therefore vision was not necessary but useful.

In the same vein, Nico et al. [108] have demonstrated that when participants had to close a triangle of which they were passively submitted to the first two sides, they overshot the distance they had to compute. Both results suggest that an overshoot of distances can occur regardless the experimental task: estimation, production, reproduction, or computation.

Moreover, when healthy participants were asked to drive without vision (in darkness) repeatedly a distance of 2 m, the produced distance was 1.55 m ± 22.5% at the first trial and 1.90 m ± 5% at the end of the trials (e.g., [77]). Therefore, without visual information the production of distance is always overperceived (i.e., undershot). Similarly, the reproduction of 2 m distance via active movement (walking) without vision, is characterised by overperception, i.e., the participants undershot that distance (e.g., [83]).

Altogether, these data are compatible with neurophysiological findings which show that a vast network of signals including visual, vestibular and somesthetic ones reaches the medial superior temporal area (e.g., [27]), the ventral intraparietal area (e.g., [115]), the frontal [5], and prefrontal cortex during passive/active forward navigation (Angelaki et al. 2006), cortices which are important for spatial linear navigation.

In the previous study, because of constant velocity the vestibular afferents were minimised. The somesthetic information is characterised by precise somatotopy which leads to an appropriate body representation in space. When visual

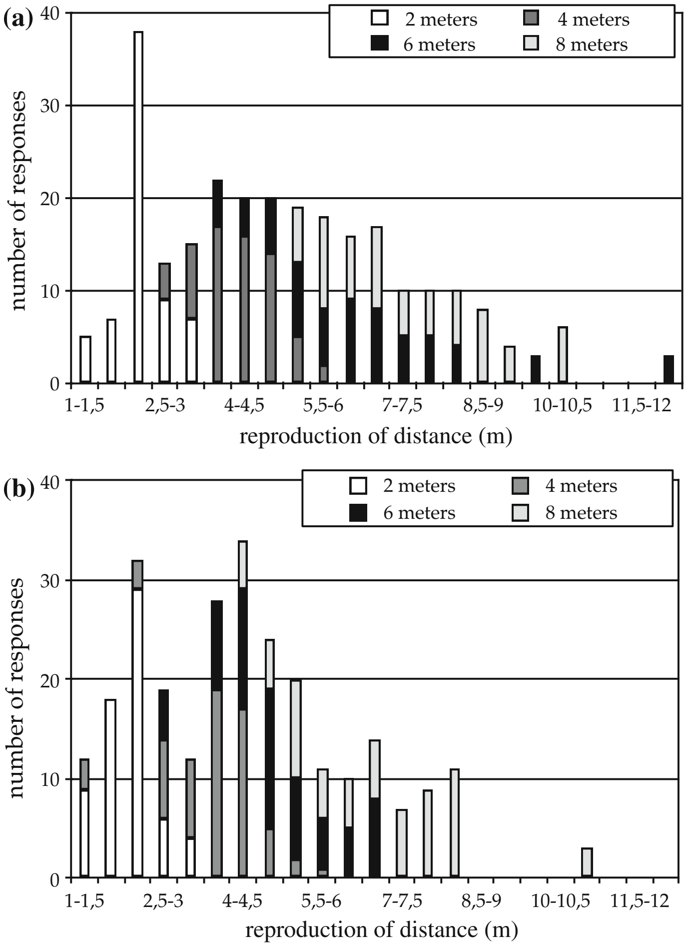


Fig. 9 Distribution of the responses **a** "with vision" and **b** "without vision", following the four traveled distances (from [75])

information is combined with somesthetic information ("with vision" condition), the visual available information predominates (and dampens the other signals) the elaboration of body representation in space. As a consequence, during visual navigation the perception of somesthetic information is impoverished which leads to overshoot. When only somesthetic information is available ("without vision" condition), the participants undershoot the long distances. In other words, path integration is not successfully achieved for long distances, where external cues are certainly useful (e.g., [75]).

The data also reflect a consistent combined effect of visual and somesthetic information with an overall higher influence of visual cues during spatial linear navigation. With such results, it seems that working visuospatial memory and planning requiring multimodal processes in brain contribute to the navigation of distances (e.g., [115]).

In sum, it seems that the brain consistently weights internal representation of body information that is on the base of spatial navigation. Under passive and active navigation, the perception of ego motion is assisted by covariant signals coming from visual, vestibular and somesthetic proprioceptive systems.

10 Conclusion

Children's and adults' common daily activities necessitate passive and/or active movement within the environment, which are possible because of the development of the internal representation of the body. Accurate linear and circular ego motion perception of the body is critical. The reported studies have provided evidence that passive and/or active ego motion is possible not only because of the integration of various information, visual, vestibular and somesthetic (exteroceptive, proprioceptive, interoceptive) but also because of cognitive, attentional, and memory processes.

Of particular importance is the visual information available during ego motion. Spatial navigation in the absence of vision, in blind persons, has specific influence in their cortical activity and behavior. Indeed, blind persons have a greater ability than blindfolded sighted persons in utilising auditory information for ego motion. During ego motion imagery in sighted individuals, a functional magnetic resonance imaging (fMRI) study has showed deactivations of vestibular areas, in the posterior insult and in temporal cortex. Structures such as somesthetic cortex, parahippocampal and fusiform gyri are activated. As opposed to sighted persons, totally blind individuals did not show activations in parahippocampal and fusiform areas. In addition with the aforementioned areas, blind persons showed activations in the superior temporal gyrus, somesthetic and primary motor cortical areas with during the same imagery task (e.g., [141]). It seems that blind individuals rely more on vestibular and somesthetic feedback for ego motion control than do sighted subjects. Taken together, these findings underlie once more the significant and synergic effect of visual inputs in the vestibular and somesthetic contributions to ego motion in space.

Associated with visuo-vestibular and somesthetic interactions, the above data relative to sighted and blind persons can potentially contribute to the spatial navigation of humanoid robots. It is well known that during ego motion robots generally deviate from their trajectory due to uncertainty in both equilibrium and position. From neuro-anatomical view point, visuo-vestibular and somesthetic afferences are directly connected with the cerebellum which in turn is interconnected with both subcortical and cortical areas. This vestibulo-cerebellum-cortex pathway is critically involved in adaptive changes in gravitational environment. Changes in position can provide noticeable challenges to the conservation of balance and cardiovascular activity as the vestibular system is partly responsible for the regulation of blood pressure. The vestibulo-sympathetic responses integrate various sensory signals reflecting body position in space, somesthetic and visual information. Even if the integration of the aforementioned signals along the three body axis is crucial for self-position and balance, visuo-vestibular and sympathetic responses along the sagittal and vertical body axes could be considered in order to make potential adjustments to robot autonomous navigation. A top-down organisation associated to visuo-vestibular and somesthetic pathway along these two axes contributed to body consciousness, i.e., ego-position and equilibrium, could afford a minimalistic neuromorphic basis in order to improve safe and reliable navigation of humanoid robots.

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Part III
Mobility of the Visually Impaired

Orientation and Mobility Training to People with Visual Impairments

Mira Goldschmidt

1 Introduction

There is consensus in the specialized literature that mobility is an important part of everyday life, and that impairment to mobility affects the quality of life [4, 12, 24, 36]. Independent travel is a well-known challenge for visually impaired persons (that is, those who are blind or have low vision). People with visual impairment experience difficulties moving around dynamic environments and in unfamiliar areas. The goal of orientation and mobility training is to prepare the person with visual impairment to travel independently in any environment, familiar or unfamiliar.

Training in orientation and mobility refers to the skills and techniques required for independent and safe travel by persons who are visually impaired [18].

Mobility has been defined as the act of moving through space in a safe and efficient manner [13]. Orientation has been defined as “knowledge of one’s distance and direction relative to things observed or remembered in the surroundings and keeping track of these spatial relationships as they can change during locomotion” [4].

Training in orientation and mobility aims to increase the skills of moving in the environment in a safe and efficient way. Orientation and mobility specialists, a specific profession to blindness and low vision, provide instruction to people with visual impairment helping them to develop or relearn the skills and concepts they need in order to travel safely and independently.

This chapter begins by presenting the orientation and mobility training to people with visual impairment. The chapter describes the specific mobility challenges of

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people with visual impairment as well as the strategies and techniques used to improve orientation and mobility. The chapter also describes the use of mobility devices helping persons with visual impairment to travel safely. More information about researches and experience of practitioners in the area of orientation and mobility can be found in Wiener et al. [42].

2 Population

According to the World Health Organization, 285 million people are estimated to be visually impaired worldwide. The visually impaired population refers to persons with low vision or with blindness. The population of people with low vision is much larger than the population of people who are totally blind. 39 million people are blind and 246 million have low vision.

According to the International Classification of Diseases—10 (Update and Revision 2006), there are four levels of visual function

1. Normal vision
2. Moderate visual impairment
3. Severe visual impairment
4. Blindness.

Moderate visual impairment, combined with severe visual impairments is grouped under the term "low vision". Approximately 90% of visually impaired people live in developing countries.

According to the WHO, the major causes of visual impairment worldwide are

- Uncorrected refractive errors (myopia, hyperopia or astigmatism), 43%
- Unoperated cataracts, 33%
- Glaucoma, 2%.

About 65% of all people with visual impairment are aged 50 and older. As the population ages, the number of people with visual impairment continues to grow.

According to the national federation of the blind, there are 5.5 million seniors in the United States who are blind or visually impaired. Only 1% of the blind population was born blind. The majority of visually impaired people in the United States lose their vision later in life because of age-related macular degeneration, glaucoma and diabetes. Age-related macular degeneration (AMD) is a leading cause of vision loss in older adults [17].

In macular degeneration the central vision deteriorates, resulting in blurred vision. Glaucoma causes damage to the optic nerve through pressure, compromising first peripheral vision. Diabetic retinopathy occurs when diabetes damages the tiny blood vessels inside the retina (Figs. 1, 2 and 3).

Fig. 1 Simulation of macular degeneration: a blurred image with a *dark spot* in the centre

Fig. 2 Simulation of glaucoma: a blurred image with a sharply focused area in the centre

Fig. 3 Simulation of diabetic retinopathy: a blurred image with *dark spots* throughout

People with vision loss may have hearing loss or physical, health or cognitive impairments. The special challenges to orientation and mobility specialists when teaching people with visual impairment and other disabilities will not be discussed in this chapter, but the use of new technologies in these situations might be very important.

3 Orientation and Mobility Instruction

The goal of orientation and mobility training is to prepare the person to travel in a variety of environments, both familiar and unfamiliar, and to increase the skills of moving in the environment in a safe and efficient way. Training in orientation and mobility develops the ability to understand one's position in space in relation to the external world and improve the ability to travel independently. Orientation and mobility training began after World War II, when techniques were developed to help veterans who had lost their sight [42].

Nowadays, training in orientation and mobility is given to people of all ages: infants, children, grown-ups and elderly. The orientation and mobility training program has to be tailored to the student's capabilities and level of functioning, and individualized programs are developed to meet the needs of each student. Successful orientation and mobility training involves a lot more than the use of a long cane or a guide dog. Training to improve the travel skills and strategies of individuals who are visually impaired will be explained in the next pages. After describing the orientation and mobility instruction for people with blindness, we will describe the specific orientation and mobility training program for people with low vision.

3.1 Orientation and Mobility Training for People with Blindness

People with normal vision can see about 180° of their environment at a glance. There is no other sense that can collect and process the same volume and richness of information as quickly as sight can. The primary differences between sighted and blind travel are the speed, volume, detail and distance from which auditory and tactile information are obtained and processed [9]. Estimates suggest that as much as 80–90% of ones' information is obtained through vision. Vision provides more useful spatial information than nonvisual spatial information.

The totally blind person has major problems in orientation and mobility and is at a disadvantage compared to the sighted pedestrian. He develops strategies and techniques in order to travel safely in the environment and uses many types of nonvisual information in place of visual information, but requires additional time in walking an unfamiliar route and crossing streets.

According to the specialized literature comparing the blind and the sighted [37–39], the long-term blind has difficulties in spatial, perceptual and conceptual abilities. The blind incorporates fewer external references and uses more egocentric information in mobility.

In a survey [25], it was found that the most frequent travel difficulty reported by blind and partially sighted people included a lack of confidence in going out alone, going to unfamiliar places and meeting obstacles in the environment, and fears about busy traffic.

Instruction in orientation and mobility starts with an assessment phase. The instructor must consider psychosocial, sensory, motor, perceptual, cognitive and environmental factors in the choice of instructional techniques and in the development of the training program. After setting the goals of the orientation and mobility training, pre-cane skills and techniques are taught prior to instructions on the use of the cane. Generally, the lessons progress from the most simple to the more complex. First, indoors environment, which is easier to control, followed by outdoors environment. Orientation and mobility training is usually given on a one-on-one basis, so that it can be adapted to the student's personal abilities.

A systematic curriculum of orientation and mobility training can be found in the literature [13, 15, 18].

3.2 *Pre-cane Skills and Techniques*

3.2.1 Sighted Guide Techniques

The instruction of totally blind adults starts usually with the sighted guide technique. Using this technique, the student walks one half step behind the guide and gets kinaesthetic and proprioceptive information while moving with the sighted guide. The guide takes the responsibility for orientation and for protection from obstacles, while the student gets used to moving safely through the environment. The student gets information from the guide about the sensory clues, spatial and environmental concepts which are necessary for orientation. While following the sighted guide, the student also receives information about the characteristics, identity and position of objects in the environment. He also learns how to judge distances and to interpret context and landmarks.

The student follows the guide movements and learns the concepts' prerequisites for establishing orientation and planning routes to travel. Some examples of spatial and environmental concepts which are necessary for orientation are: left, right, front, back, straight-line concept, parallel, perpendicular, right angle, etc. The student learns how to interpret the information he gets from the guide's movements. He learns how to change direction and how to negotiate stairs. By using the sighted guide technique, the student can develop skills and get preparation for independent travel.

3.2.2 Self-protection Technique

Self-protection is a technique used by people with visual impairment, to allow them to travel efficiently and independently in familiar indoor environments, affording them maximum protection without the use of a mobility aid. The forearm, when held in the correct position in front of the body, acts as a shock absorber and reduces the risk of injury. The self-protection technique enables the person to detect vertical objects at the upper region of the body and at the waist level.

3.2.3 Trailing Technique

The purpose of the trailing is to facilitate the student's maintenance of a straight line of travel (for example in hallways and corridors) and to locate a specific object. The student follows with his fingers a line of travel (for example the wall), so that he can keep constant contact with the environment and can gain advance information about an unfamiliar area (location of stairs, level changes, etc.).

3.2.4 Accurate Turns

The student learns how to make accurate turns and how to travel in open doorways and to establish a straight line of travel so that he will be able to familiarize himself systematically with a particular environment.

3.3 Mobility

Without mobility aid, the blind person's movements will be severely restricted. The most prevalent devices that are used by people with visual impairment are the long cane and the guide dog. Long cane is the primary tool utilized by the visually impaired people in orientation and mobility. The long cane was introduced by Richard Hoover in the late 1940s, replacing the traditional short wooden cane. Richard Hoover introduced the technique of moving the cane from side to side with the tip touching the ground in front of the trailing foot. Systematic training of guide dogs began in the eighteenth century, but guide dogs became widespread only after the First World War [40].

3.3.1 Long Cane Techniques

The cane skills enable the person to travel safely, efficiently and independently, in a familiar or unfamiliar environment. Strategies for using the cane in a systematic way are essential. The function of the long cane is to preview the immediate environment for objects on the path of travel, and to preview changes of the surface of travel. The student can perceive the material, slope, elevation of an upcoming walking surface, the location and dimension of the obstacles. The long cane provides detection of obstacles and information about the travel path in advance, as it allows detection of obstacles within a 3-ft (about 90 cm) range. To clear the path ahead, the cane is swept from left to right, synchronized with the steps of the user. If an obstacle is detected the cane user has to react quickly to avoid collision. When the cane contacts the ground, it can also provide information concerning objects on the side of the path through the acoustical reflections that result from tapping the ground with the cane tip. The trained pedestrian can get haptic and auditory inputs from the cane which will help him map the environment. A systematic curriculum of instructions is used by the orientation and mobility specialists.

Different cane techniques are used to guide the locomotion.

For example, the diagonal technique (used mostly in a familiar indoor environment), the touch technique (used for example to detect drop-offs and objects in the vertical plane in familiar or unfamiliar environments), the touch and slide technique (used to detect textural changes, subtle drop-offs and blended areas perpendicular to the line of travel), the touch and drag technique (used for example for locating bus poles or for street crossing alignment), the three point touch technique (used for example to follow the curb of a street when no sidewalk exists), and the ascending and descending steps technique.

With the long cane techniques, the student gets protection from obstacles and gains environmental information. The cane serves also as an indicator to drivers and sighted pedestrians that care should be taken in the presence of such a device.

The limitations of the long cane are such that small objects can be missed by the sweep of the cane, and the overhanging obstacles cannot be detected by the cane. The body from the waist up is vulnerable to physical contact with objects or people [32].

3.3.2 Guide Dogs

The next most common mobility aid after the cane is the guide dog. Completion of a mobility training course is a prerequisite for using a guide dog. Guide dogs are trained to avoid all obstacles (also overhanging obstacles) and the blind pedestrian needs to assess the dog's behaviour and interpret it to remain safe and oriented. Using a guide dog facilitates travel in open areas, in off-road conditions, in snow and parks. At street crossings, it is easier to maintain the line of direction with a guide dog. As guide dogs are trained to avoid obstacles, they provide minimal tactile contact with the environment and might deprive the blind pedestrian from information that could be helpful for his orientation.

Guide dogs are not appropriate as mobility aids for all blind people. The training process is physically vigorous, and the walking speed with a guide dog is much faster than that with a cane. The blind person needs to have good coordination, strength and balance. The training in orientation and mobility is also useful to the guide dog user. For example, with orientation skills, ability to align with traffic sound or the ability to recover when disoriented.

With the long cane techniques or with a guide dog, the student can assume responsibility for travelling safely, but he also needs sensory training. Sensory training includes developing the student's ability to utilize all of his available senses for orientation. Efficient use of tactile and auditory information does not always develop automatically and the student with visual impairment needs some exercises to increase the sensitivity and the application of his remaining senses.

3.3.3 Street Crossings

Street crossing is associated with increased risk of injury. The most important aspect of street crossing is safety and it is an important part of the student's orientation and mobility training. Generally, the lessons on making traffic judgments progress from the simplest streets crossings to the more complex streets crossings.

The student is trained to cross streets in a safe, efficient and systematic manner. He learns how to locate the street and how to analyze the intersection (for example, the location of the crosswalk, the direction of the opposite corner, the number of intersecting streets, the width of the street, etc.). The student has to learn how to line up and make a straight crossing. He learns how to prevent veering while crossing the street and how to recover from veering and reorient himself to the desired position. He also needs to learn how to analyze irregular intersections and to judge and determine the good moment for safe crossing. The use of technologies like detectable warning surfaces and accessible pedestrian signals helps the blind traveller with street crossings. The visually impaired pedestrian has to deal with complex environments like roundabouts and unusual geometric shapes of intersection and orientation and mobility training in these situations is essential. Quiet cars are presenting challenges to pedestrians with blindness and adapted strategies are necessary.

3.3.4 Residential and Commercial Areas

The student is trained to travel in residential and commercial areas. He learns how to use escalators, elevators and revolving doors. The student exercises travelling day and night in specified conditions like congested areas and subways.

3.3.5 Transportation System

The student is introduced to the use of public transportation. He learns how to use the various types of transportation systems and develops the needed strategies to plan and to travel independently. The student learns how to deal with unexpected events (for example, when he gets off at the wrong station) and emergency situations. The use of new technology, like audible arrival and departure information systems and online trip information improved access to public transportation.

3.4 Sensory training

The development of orientation skills enables the blind pedestrian to get familiar with unfamiliar environments. The student learns how to get a line course from an object or sound to facilitate travelling in a straight direction toward an objective. He also learns how to reorient himself to a desired position (recovery) after drifting away from the desired line of travel.

Orientation is maintained by the use of a number of skills and information gained from the environment through other senses. According to Long and Giudice [19] there are four fundamental aspects of spatial orientation: information collecting, the use of strategies for following familiar routes, the use of cognitive maps, and the application of strategies to solve problems.

Persons with visual impairments are able to gain orientation and to maintain this orientation while moving from one part of the environment to the other by using a combination of the remaining sensory information. They use landmarks and clues to establish and maintain orientation. The landmarks and clues are used as reference points to locate specific objectives and for perpendicular and parallel alignment needed for a straight line of travel.

A landmark can be any familiar object, sound, odour, temperature or tactual clue which is constant, easily recognized and with a permanent location in the environment. A clue is any visual, auditory, tactile, olfactory or kinaesthetic information that can help the blind pedestrian to obtain direction and to determine his position in the environment. As he needs to learn to negotiate his surroundings, the student has to develop his capacities of utilizing the remaining senses in establishing his position and relationship to all other significant objects in his environment. The sensory training he gets can help him to utilize the remaining senses to the optimum. For example, at home familiar sounds can help him locate objects, or outdoor traffic noise can help him to orient himself. The changes in sound as he moves around can also be used for orientation. He can also continually visualize his environment and his location within that environment.

The principal sensory cues for spatial location are available to the blind through touch for near space and through sound for far space.

Touch is used to identify objects encountered during travel and to recognize familiar landmarks. Tactile exploration and the ability to use tactile and haptic information accurately and efficiently have to be developed. Touch is used to identify objects in the environment during travel and to recognize landmarks.

As sound localization and sound discrimination are important auditory skills in orientation and mobility, an auditory training program is proposed so that the student can learn how to interpret the sound and determine, for example, the approximate size of a room and the location of the doorway. The student can perceive the direction of a sound source and localize the distance of sound sources and use it, for example, for street crossing. He can also track movements of vehicles by the sounds they produce and locate signs and poles by the sound they reflect.

Many blind persons develop echolocation, the awareness of the presence and locations of objects in the environment without vision. Echolocation can help the pedestrian with visual impairment to avoid large obstacles and locate openings along walls before making physical contact with them. Lower frequency sound cues are particularly important in echolocation. Self-produced sounds enhance the use of reflected sound for mobility, and persons with visual impairment also develop the capacity to produce sounds that are optimal for perception.

When visual, auditory, or tactile information is not completely accessible, pedestrians with visual impairment can use proprioceptive and kinaesthetic cues for mobility. The kinaesthetic senses, based on proprioception, can provide nonvisual information that can help the student to remain oriented as he walks through familiar surroundings [21]. Training the kinaesthetic sense might help the student to maintain his line of travel and improves measurement of turns and measurement of walking distances.

Training the compensatory use of environmental olfactory cues is also useful in orientation, as in some circumstances the perception and discrimination of odours can help identifying places like restaurants or others shops. The use of cardinal directions in mobility is important for independent travel. Tactile or audible compasses are used in orientation and mobility training to establish a line of travel, since compass' directions add stability to the environment and are constant. Tactile compasses have a raised dial on which an arrow represents north, while east, south, and west are represented by Braille letters. Electronic compasses provide the pedestrian with spoken announcements. The use of electronic orientation aids is discussed later in this chapter.

Cognitive maps, which are mental images of the information about routes, are essential for independent travel of people with visual impairments. Orientation and mobility specialists use orientation aids like tactile maps and large-print maps, models and route descriptions for the development of spatial concepts and cognitive maps. Maps for visually impaired people have to include only essential information. Training in the use of tactile maps and models can enhance understanding of the spatial and environmental concepts and can improve travelling in novel areas and estimating travel time. Tactile maps and models are good alternatives to visual preview but the ability to use them effectively and efficiently has to be developed. Orientation and mobility specialists teach strategies for map reading. Concepts like linear continuity and directionality, symbolic representation, scale and shape are necessary for map reading. Scanning systematically, identifying symbols, tracing line symbols and recognizing shapes are also some of the skills that orientation and mobility instructors teach to make optimal use of maps. More information about teaching the use of maps in orientation and mobility can be found in Bentzen and Martin [2].

Congenitally blind people do not have the same rehabilitation needs as people with acquired blindness. Congenitally blind children might have gait and posture problems if they do not get early intervention. They need to develop basic concepts and orientation skills. Millar [23] suggested that congenitally blind people have less precise sources of spatial information because they base their spatial knowledge more on proprioceptive and kinaesthetic information. People who are congenitally blind have a different mental representation of the spatial layout compared to people who become blind. A person who was born blind will put locations in relation to each other without having a concrete image of it, while a person who is a late blind will form an image based on images that he has seen before. According to Thinus-Blanc and Gauner [34], the age of onset of visual impairment has no effect on egocentric spatial tasks, but when tasks require a more allocentric frame of reference, there are differences in performances between groups of people who lost vision early in life and those who lost vision later in life.

3.5 Orientation and Mobility Training for People with Low Vision

Mobility training program for a low vision person has to be preceded by assessment of the student's visual functioning in a variety of conditions and in a variety of settings. The functional evaluation with the remaining vision is necessary in order to adapt the orientation and mobility training to the person with low vision, so that he will be able to use the remaining vision for navigation to its fullest potential.

3.5.1 The Specific Mobility Needs of People With Low Vision

The majority of people who have a visual impairment have some residual vision [8]. WHO [41] define low vision as the inability, even with corrective lenses, to clearly see at a distance of 6 m (20 ft) what individuals with normal vision can clearly see at a distance of 18 m (60 ft).

Most of the people with visual impairment have some usable vision for navigation. The field of low vision mobility is about five decades old. The idea that people with low vision have the same rehabilitation needs as the blind people has been changed within the last decades. Orientation and mobility training for people with low vision is different from the trainings designed for people who are totally blind. Although many of the trained techniques and skills are useful for both populations, persons with low vision need a special training program designed at increasing their visual functioning in orientation and mobility.

Reduced visual acuity is more common than reduced visual field. Table 1 describes the common pathologies and their functional problems.

The mobility problems associated with reduced visual acuity might be different from the mobility difficulties associated with reduced visual fields. Some students with reduced visual acuity do not have the ability to read or to recognize faces and cannot detect stairs and curbs. Students with a restricted visual field may see obstacles but lose perspective and might not be able to avoid them. Glare and depth perception are the most frequent functional difficulties. Some students do not have the ability to judge speed and direction of traffic. In most of the pathologies causing low vision, people suffer from glare, loss of depth perception and fluctuating vision and need orientation and mobility intervention.

Turano et al. [35] had studied the distribution of perceived ability for independent mobility in people at various stages of Retinitis Pigmentosa (RP). They found that four of the six most difficult mobility situations were related to: lighting conditions, walking at night, adjusting to lighting changes, walking in dimly lit indoor areas, and walking in high-glare areas. They also found that in the situations such as moving about in the home and walking in familiar areas, the RP subjects reported little or no difficulty. According to the authors, this finding implies that

Table 1 Common pathologies and their functional problems

Pathology	Glare	Visual field loss	Scotoma	Night blindness	Light adaptation	Fluctuating vision	Depth perception
Achromatopsia	x				x		
Albinism	x				x		
Aniridia	x				x		
Aphakia	x						x
Cataracts	x				x	x	x
Coloboma	x	x					
Diabetes	x	x	x		x	x	x
Glaucoma	x	x		x	x	x	x
Hemianopsia		x					
High myopia	x	x					x
Keratoconus	x					x	x
Macular degeneration	x		x			x	x
Optic atrophy	x	x	x			x	x
Retinal detachment	x	x				x	
Retinopathy of prematurity	x	x	x			x	x
Retinitis pigmentosa	x	x		x	x	x	x

Source Geruschat and Smith [10, pp. 63–83]

vision may not be as critical when people already have a mental representation of their surroundings and when the objects in those surroundings remain stationary.

Smith et al. [29] had studied the perceptions of the most difficult mobility problems in persons with low vision and in orientation and mobility specialists. The individuals with low vision's perceptions of their five most difficult mobility problems were: drop-offs (negotiating steps, curbs, and ramps), lighting conditions and adapting to changes in lighting, street crossing (inability to distinguish the colour of traffic lights and crossing without traffic lights), changes in terrain (broken or uneven sidewalks, street, and surfaces), and obstacles (low-laying objects, head-high and low-hanging objects). When orientation and mobility specialists were asked to list the five more difficult mobility problems of the "low vision population in general", they mentioned the same top five problems. They differed only in the order of the problem; with "lighting conditions" exchanging place with "drop-offs" to become the most commonly cited problems.

These findings suggest that the long cane or other electronic devices could be used to detect curbs and ramps and help in negotiating steps and this is the case also for people with low vision.

Long et al. [20] had also described the difficulties caused by lighting conditions, adaptations to different conditions of illumination, and the negative effect of reduced lighting on mobility. These results also point to the need of devices to help in the travel difficulties cause by varying conditions of illumination.

Most people with low vision are elderly, sometimes with other impairments, and do not make effective adaptation to blindness as do younger persons. According to Campbell et al. [5] older people with visual impairment have an increased risk of falling. Other studies [6, 33, 31] showed that AMD has been associated with falls. Orientation and mobility instructors assess the home environment and provide environmental modifications to prevent falling.

Sengupta et al. [28] showed that patients with low vision due to macular degeneration do not engage in physical activity nor do they leave their homes as much as normally sighted individuals.

According to Glen et al. [11], patients with low vision due to glaucoma reported problems relating to mobility (walking and driving), navigating around obstacles (including steps and uneven ground) and their general interaction with people and places.

Khan [16] showed that persons with low vision due to diabetic retinopathy often experience difficulties with activities such as identifying faces, reading bus numbers from a distance, reading small and low contrast print, intolerance to light, and difficulty in moving outdoors.

According to Geruschat and Smith [9], most of the students with low vision experience fluctuation in the quality and clarity of what they see. Vision provides more useful spatial information than other senses and pedestrians with low vision get impoverished visual information and sometimes confusing information.

These results also point to the need of training in different situations of travel difficulties. The pedestrian with low vision has to decide when the visual information is reliable and sufficient or when the other sensory information is more reliable for travelling in a safe manner. When the pedestrian with low vision is looking down most of the time instead of using his vision to get visual information from the environment, it affects his security in navigation, and the use of a long cane is proposed. Sometimes a combined use of low vision and the long cane is needed. The cane helps to improve vision efficiency for orientation and can augment assurance and independent mobility. Some people with low vision use the cane only for travel in heavy glare, or for night conditions, or in crowded places and unfamiliar areas. The long cane can be an important tool for enhancing visual efficiency. Geruschat and Smith [9] explain that one of the most important aspects of instruction in low vision mobility is teaching the student the critical variables to assess if the use of the long cane is necessary. People with low vision also use a short cane as an indicator to sighted persons that attention should be given in the presence of a person using such a device.

3.5.2 Training for People with Low Vision

The instruction in orientation and mobility starts often indoors in a controlled environment and is then trained outdoors. Barraga and Morris [1] described a program to develop efficiency in visual functioning and showed that people with low vision can learn how to better use their remaining vision. Orientation and mobility specialists work on enhancing visual experiences by working in a variety of environmental situations.

Some people with low vision experience difficulties performing visual tasks and need visual training to maximize visual efficiency and to develop the use of vision for mobility. As the visual localization and visual identification of objects and people in movement can be challenging in changing surroundings, it is often necessary to teach the low vision pedestrian to scan, to follow moving objects and to interpret confusing visual information. Tracing, scanning and tracking are some of the visual motor skills that the student with low vision has to develop in order to maximize the use of his functional vision.

The student with low vision also has to develop techniques and strategies to maximize safety and efficiency of movement. Instruction in low vision mobility includes strategy like monocular depth and perception of visual cues that could help him judging changes in elevation. People with central visual field loss (for example in age-related macular degeneration) have to develop eccentric viewing. Some students automatically develop eccentric fixation and some students need instruction in locating and using eccentric viewing. The training of the use of eccentric viewing is necessary for a clearer view at traffic lights, recognizing or reading street signs, building's and bus' numbers. Students with peripheral visual field loss (for example in Retinitis Pigmentosa, Glaucoma or Hemianopia) have to be trained at the scanning of objects.

Most of the students with low vision have to develop strategies for increasing light and decreasing glare in order to maximize their remaining vision.

The use of optical and non-optical devices can improve orientation and mobility. The use of sun glasses as well as a sun hat or a visor is proposed by orientation and mobility specialists to improve vision under conditions of glare. To improve vision under conditions of low light or no light, orientation and mobility instructors propose the use of wide and bright beam lights' sources. Night training in orientation and mobility is very important to people with night blindness (for example in pathologies like Retinitis Pigmentosa and Glaucoma). Although contrast sensitivity and visual acuity are related, people with relatively good visual acuity might have difficulties at nightfall and need some training in low contrast situations. Some people with low vision travel in night time more safely than in the daytime and get a short night training in orientation and mobility.

Telescopes are often used in orientation and mobility, as they can improve distance visual acuity and can be used in orientation and mobility for recognizing traffic lights, reading street signs, numbers on buildings, and bus numbers. Using a telescope improves visual acuity but reduces visual field and reduces the amount of light entering the eye. Orientation and mobility instructors have to train the use of optical devices and teach how to reduce blurred images, how to attain maximum acuity and how to deal with restricted visual field of the telescope. The student learns how to localize stationary objects with the telescope and how to focus on a moving object at a constant distance. He also learns how to follow an object in movement and refocus continuously. Finally, he learns how to look for a detail on moving objects. Fresnel and Pelli prisms can also assist students with restricted visual field and good visual acuity to increase visual scanning. Reversed telescopes can help students with restricted visual fields and good visual acuity to widen the viewing area.

The use of near vision optical and electronic aids can be helpful for navigation. During orientation and mobility training, the use of near vision optical and electronic aids is trained also for reading maps, reading time tables or preparing lessons.

Many students with low vision need training in using visual and nonvisual information together. They have to learn how to trust the nonvisual information and how to integrate the use of both types of information.

3.6 Environmental Modifications

Environmental modifications indoors are proposed to facilitate orientation and to enable safe travel. Some of the modifications include: reducing glare, improving lighting, painting the edge of steps with a contrasting colour, avoiding environmental hazards, etc.

Orientation and mobility specialists are also involved in environmental modifications in complex pedestrian areas to facilitate orientation and to prevent accidents. Some of the environmental modifications are the use of colour and contrast cues or the use of consistent sign style and placement, the use of tactile signs, elimination of wall-mounted objects and pole-mounted objects, making stairs safe and easy to negotiate, etc. The use of technological solutions in pedestrian areas to enhance mobility for blind and partially sighted people is very useful. For example, the provision of an audible signal or the uses of linear surfaces to indicate crosswalk locations are useful cues for finding a crossing in an unfamiliar area.

4 Electronic Travel Aids and Electronic Orientation Aids

The most prevalent devices that are used by people with visual impairment are the long cane and the guide dog. As new electronic aids emerge, the cane and guide dog are becoming part of a larger collection of potential tools adapted to the needs of persons with visual impairments. Electronic travel aids and electronic orientation aids can be used with a cane or a guide dog. The electronic travel aids and electronic orientation aids were developed so they can provide solutions to some of the limitations of the traditional aids in orientation and mobility.

The choice of electronic travel aids and electronic orientation aids are often determined by the users with the guidance of orientation and mobility instructors. In order to use the electronic travel aids and electronic orientation aids, it is very important for the student to have a strong foundation in orientation and mobility skills.

Orientation and mobility instructors have to evaluate the travel needs and the characteristics of candidates for using electronic travel aids and electronic orientation aids. Smith and Penrod [30] present some characteristics of candidates to be considered for using electronic travel aids and electronic orientation aids. For example, the travel history of the candidate, his level of competence, his confidence with the cane or the guide dog, the amount of remaining vision of the candidate, the physical ability of the candidate to utilize the device safely. Other considerations are the geographical area in which the candidate travels, cosmetic acceptability, subtlety of the signal output, attitudes and reaction of family and public. According to the authors, "the obvious factors to be considered in matching a person to a device are auditory discrimination ability, tactile discrimination, visual acuity, motivation, and cost benefit". Orientation and mobility specialists need to be involved in the design of electronic travel aids and electronic orientation aids and make sure that the travel aids promote independent travel in any situation.

Electronic travel aids and electronic orientation aids may provide additional safety, fluidity of travel and awareness of landmarks. Penrod et al. [26] explain that it is not easy to show the improvement in mobility performance by using an electronic travel aid. Smith and Penrod [30] stated that electronic travel aids and electronic orientation aids can offer advantages to many people with visual impairment, but cost, requirement for training, lack of trained orientation and mobility specialists, and the effectiveness of other devices have all limited the number of users. According to Smith and Penrod [30] the ideal length of training the use of electronic travel aids depends on several factors and it ranges from 20 to 120 h, depending on the student, the device and the travel environment.

The use of electronic aids in orientation and mobility can be useful for people with visual and additional impairments.

4.1 Electronic Travel Aids

Electronic travel aids have the purpose of enhancing mobility for the blind pedestrian. Blasch et al. [3] defined electronic travel aids as "devices that transform information about the environment that would normally be relayed through vision, into a form that can be conveyed through another sensory modality". The electronic travel aids send energy out into the environment and receive the reflected energy for interpretation by the pedestrian.

According to the National Research Council (1986) as cited by Smith and Penrod [30], the most essential information needs of the pedestrian are

1. Detection of obstacles from ground level to head height for the full body width.
2. Information about the travel surface
3. Detection of objects bordering the travel path
4. Distant object and cardinal direction information
5. Landmark location and identification information
6. Information enabling mental mapping of an environment

Electronic travel aids, by giving audible or tactile outputs or both can provide obstacle detection and can provide information about the travel path in advance. Some electronic travel aids detect obstacles and landmarks that the cane might miss and some electronic travel aids replace the function of the cane. As was described before, the information that the long cane provides is transmitted at the moment of contact with the object and not before. The use of electronic travel aids enhances the preview provided by the long cane and might reduce anxiety and embarrassment related to unwanted personal contact with objects or with people.

Furthermore, the electronic travel aids may provide information that would never be available otherwise, for example the appreciation of the height and size of buildings and trees. They can extend the student's knowledge of self-to-object and object-to-object relationships. The electronic travel aids are very useful for students who are learning concepts (for example, congenitally blind children).

Farmer [7] describes two categories of electronic travel aids: primary and secondary. If the device could be used to replace a mobility system, for example a cane, guide dog or human guide, it was considered a primary device (provides surface preview and obstacle preview) and if it must be used in combination with a cane or guide dog to ensure the detection of stairs, curbs and drop off, it was considered a secondary device.

In order to use the electronic travel aids efficiently, it is very important for the student to have a strong foundation in orientation and mobility skills. When the student starts using the electronic travel aids, he usually gives his attention to the device and might ignore other sensory information. Using electronic travel aids can be tiring at the beginning and sometimes students might be frustrated and confused if the training is too fast.

Penrod et al. [27] described a curriculum with a basic model of lessons for teaching the use of electronic travel aids. The authors propose the following indoor lessons' sequence to teach the use of electronic aids by orientation and mobility specialists:

- familiarization with the aid;
- development of general proprioceptive awareness of the distance setting of the electronic aid;

- learning how to judge distance with the aid using the variability of pulse or frequency information;
- development of accuracy in relating pulse of frequency to distance;
- using the electronic aid to align perpendicularly with a wall; using the electronic aid in combination with the cane or a guide dog;
- learning how to detect and avoid overhanging objects;
- practice in travel situations the interpretation of multiple signals from the device; using the electronic aid to locate landmarks;
- detecting doorways with the electronic aid;
- trailing a wall with the electronic aid (without using the cane or the fingers);
- detecting intersection hallways with the electronic aid.

After the indoor lessons, the student gets outdoor lessons in more complex environments. The student is trained in using the electronic aid to trail outside wall, tree line or fence and to locate particular landmarks. Then the student learns how to follow specific routes, identifying salient features that may be used as landmarks, identifying and avoiding overhead and forward standing obstacles, detecting curbs and steps; identifying and avoiding other pedestrians; and at the same time maintaining safe travel techniques.

The authors explain the limits and the possibilities of electronic travel aids according to the pedestrians needs. For example, electronic travel aids which use tactile-haptic vibrations may be more suitable for a student who has a hearing loss but does not have any problems with neuropathy, and electronic travel aids which use audible pulses may be more adequate for student with neuropathy problems.

4.2 Electronic Orientation Aids

Electronic orientation aids are devices that give new possibilities for locating destinations for persons who are visually impaired. Electronic orientation aids are devices that locate the pedestrian within a global or local coordinate system. They use the Global Positioning System (GPS) technology and can be very useful for mobility, as it can identify and give directions to a specific address and can assist the pedestrian with visual impairment in orientation. Such devices receive a GPS signal and use it to compute the position of the pedestrian. The GPS is a supplement to the long cane or to the guiding dogs and is not intended to provide detailed information about the most immediate environment. Electronic orientation aids provide a complement of orientation to other mobility devices. With the electronic orientation aids, people with visual impairment can better plan their travel and identify their location along their travel path. They can also travel independently in various unfamiliar areas. A GPS can improve travel planning and reduce travel anxiety. Guide dog users and cane users can combine the use of the GPS with the guide dog and get more information about the environment.

GPS accuracy can help the student arrive in close proximity to his final objective but cannot always announce destinations with extreme precision. The development of GPS with increased precision is essential to aid people with visual impairment.

Many students find the GPS useful also when travelling with a sighted guide or with public transportation. The use of GPS requires practice and instruction and students need to learn to use the system efficiently. They need to learn when to listen to the GPS, what to listen for and how to use the information they get from the GPS.

Many spatial concepts and skills can be trained using a GPS, and orientation and mobility specialists use it to facilitate understanding processes. One has to mention that although GPS is very useful in orientation, it cannot replace training in orientation and mobility.

According to the curriculum for teaching the use of GPS presented by Penrod et al. [27], the following lessons are proposed by the orientation and mobility specialists:

- information about the GPS network and GPS receiver technology;
- familiarization with the GPS components;
- learning how to turn the GPS on and off;
- learning to shift the volume and control the speech rate;
- learning the names and positions of all keys;
- learning to wear and adjust the GPS;
- learning to establish and check the GPS signal status;
- learning to determine compass heading for the direction of travel;
- learning about point of interest and how to create personal points of interest;
- learning about travel (pedestrian and motorized) modes and digital maps;
- learning to locate personal points of interest;
- learning about the virtual mode of the GPS for planning and for learning new areas;
- learning to identify traffic intersections;
- learning to use a dialog box and to navigate menus;
- learning to navigate and change information in the dialog box;
- learning to edit points of interests;
- learning to create pedestrian point-to-point routes;
- learning to walk point-to-point routes;
- learning how to use the rerouting feature;
- learning how to create quick routes;
- learning how to change the GPS system’s settings;
- learning to maintain and adapt the GPS system.

The GPS does not work inside buildings because it cannot establish a connection to the GPS satellites and it must be supplemented by other systems, like Wi-Fi or Bluetooth, to locate the visually impaired person.

5 Electronic Visual Aids with Augmented Vision Systems

Electronic travel aids that enhance the use of vision can be very helpful in orientation and mobility for people who have some residual vision.

Electronic visual aids were proposed for a variety of vision impairments. Luo and Peli [22] developed a head-mounted displaying device for people with restricted peripheral visual fields that was shown to significantly improve user's search performance. Different augmented vision systems provided mostly magnification and video contrast control. Other prototype devices provided image enhancement and light amplification for night vision.

These products are usually not recommended for use while walking because of the limited field of view of most devices and the difficulties adapting to high magnification vision for constant use in mobility. Google Glass could be used during mobility. Hwang and Peli [14] explored the possibility of using the Google Glass as a visual aid for people with impaired vision, by providing augmented edge enhancement. More research and development is needed in this area.

Tablets are accessible for people with low vision and are useful for gathering information in orientation and mobility as the large screen makes text and images larger. Using smart phones with cameras, GPS and compass apps are also helpful in orientation and mobility.

Many applications (apps) were developed specifically for people with visual impairments and can be divided into three categories: navigation, identification and reading. For example, some apps provide additional audible announcements and are useful for cane or guide dogs users. These apps can provide information such as the names of and distances to upcoming streets and intersections, business names and addresses as you pass them, along with the distance remaining and the direction to your destination. Colour identifier and light sensor apps can help to get more information about the environment. Some apps can be used to identify and describe objects in the closed environments for people with ultra-low vision or blindness.

Head-mounted display devices are used after retinal implantation in people with blindness. There are some commercially available products that provide visual perceptions to blind persons. People with a retinal implant are trained by orientation and mobility specialists indoors and outdoors to use their visual perception for navigation. For example, they are trained to detect ceiling lights in a hallway for improved walking, straight down the hallway, and to detect lights from windows and open doors for better orientation in a room, and also to detect the line of a crosswalk for preventing veering while crossing the street.

As mentioned earlier, the use of new technologies with people who have vision loss and other disabilities like hearing loss, or physical and health impairments, or cognitive impairments, might be very helpful. For example, the use of electronic travel aid devices by people with visual impairment who use wheelchairs or scooters might provide obstacle detection and avoid hazards and drop-offs. Another example is the use of electronic orientation aid devices with tactile output by people with hearing loss.

6 Conclusion

The chapter describes the training of visually impaired persons in orientation and mobility. The goal of orientation and mobility training is to prepare people with visual impairment to travel in a variety of environments, both familiar and unfamiliar, and to increase the skills of moving in the environment in a safe and efficient way.

The chapter explains the specific mobility challenges of people with visual impairment and the strategies and techniques used to improve orientation and mobility. The use of mobility devices helping persons with visual impairment to travel safely is also described in this chapter.

The most essential information needs of the pedestrian with visual impairment are: detection of obstacles from ground level to head height for the full body width, information about the travel surface, detection of objects bordering the travel path, location and identification of landmarks, and information enabling mental mapping of an environment.

Although the cane and the guide dog are reliable mobility aids, they have some limitations. The long cane cannot detect small objects or holes and overhanging obstacles even when proper techniques are being used. Guide dogs provide minimal tactile contact with the environment and might deprive the blind pedestrian from information that could be helpful for his orientation. Electronic travel aids and electronic orientation aids offer complementary aid to the traditional mobility aids. By giving audible or tactile outputs or both, electronic aids can provide advance obstacle detection, awareness of landmarks and information about the travel path, and might give fluidity of travel and reduce anxiety and embarrassment related to unwanted personal contact with people or objects. Furthermore, the electronic travel aids may provide information that would never be available otherwise, for example the appreciation of the height and size of buildings and trees, and can be used by orientation and mobility specialist in concept development.

The use of new technologies is an integral part of training in orientation and mobility. New technologies have revolutionized the field of orientation and mobility by giving more information than ever before to the pedestrian with visual impairment. Some of the devices are designed to help visually impaired pedestrians to travel safely and quickly among obstacles and other hazards in complex and unfamiliar environments.

As the majority of people who have visual impairment have some residual vision, the development of electronic travel aids that enhance the use of vision in orientation and mobility can be very helpful. Some devices were developed to adapt image enhancement technologies to people with low vision and to help them maximize the use of their vision in different situations and conditions. The most difficult mobility problems of people with low vision are the negotiation of steps, curbs, ramps and lighting conditions and adapting to changes in lighting, distinguishing the colour of traffic lights and crossing without traffic lights, adapting to the changes in terrain (broken or uneven sidewalks, street, and surfaces), and obstacles (low-laying objects, head-high and low-hanging objects). As fluctuating vision is also a common functional problem of people with low vision, devices with the capacity to adapt to fluctuating vision and to different mobility situations could be very useful. Electronic travel aids and electronic orientation aids may promote independent travel in any situation.

In order to use new technologies as travel aids it is very important for the student to have a strong foundation in orientation and mobility skills.

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Spatial Orientation in Children: A Tyflological Approach

Krystyna Nawrocka-Łabuś

This chapter explains the cognitive and psychological basis of teaching visually impaired children, especially when teaching them spatial mobility and spatial orientation. The tyflological approach is proposed.

The whole chapter is organized as follows.

Section 1 addresses the concept of spatial orientation and its shaping in children. Secttion 2 briefly presents some methodological topics on the work with visually impaired children when teaching them how to acquire the spatial cognition. Section 3 encompasses some open questions of spatial knowledge of visually impaired people (VIP).

1 Shaping Children's Spatial Orientation

1.1 Spatial Orientation

Orientation is the process of using our senses to determine our own position and the relationships between all major objects in the environment; orientation is to be aware of where we are.

The term spatial orientation in physical space encompasses the control of the body in relation to the environment, in relation to the location of objects, of people, being aware of sizes, shapes, and objects in space.

Tyflology is the science of mobility; Tyflos is the Greek word for blind.

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The term orientation defines the ability to recognize the space, primarily the surrounding space. Being oriented in space means to be able determine the size and shape of its components. Spatial orientation is the practical use of spatial imagination.

The above definitions are similar and refer to the orientation of all people. The differences that occur in the orientation of sighted and blind people rely on the fact that sighted orientation involves primarily vision, while visually impaired people (VIP) use other senses (hearing, touch, smell, kinesthetic sense and balance), as well as the sense specific to blind people and defined as the sense of mass.

Spatial orientation of VIP is a unique specialty. Mobility and orientation specialists are locomotion or mobility teachers (named also tyflologues after Greek word "tyflos" meaning the blind person). Teaching the self-movement and the daily activities is to not only teach self-reliance as a way to personal independence, but in the same time the way to achieve a better quality of life.

Restrictions on the free and independent movement of blind people and cognitive limitations are considered the largest and most visible barrier in human life.

Sightless navigation in space relies on:

- spatial orientation as the capability of exploring the surroundings and the understanding of the space-time relations; a crucial role is played by cognitive processes, concepts already known, knowledge of the body schema, spatial imagination, knowledge about the environment and how to manage relationship between time and distances;
- locomotion as the ability to move from place to place depending on the motor features: agility, strength, speed, endurance, balance, and a number of skills such as correct walking, running, maintaining direction, homing, and space layouts understanding.

The practice requires learning of orientation and locomotion, which are mutually dependent. The student personality plays an important role in learning orientation and independent mobility. Not only intelligence is important, but also self-confidence, motivation, decision-making skills, mental strength, and past experience.

Achievements in spatial orientation allow:

- to move independently (without external help) which in returns helps developing spatial knowledge, the new emotions (acquire new qualias), and enables to observe new phenomena, to realize live new experiences, to learn and to exploit new experiences;
- to experience the satisfaction of overcoming difficulties, to develop self-confidence, perseverance in goal achievement, and to increase his/her self-esteem;
- to become more efficient and physically fit, to gain better coordination, and overall appearance, attitude, and his/her own way of functioning;
- to be independent, and thus having a chance to achieve better balance between their private and professional life.

The overriding long-term objective, which is to help VIP achieve their optimal development, giving them and their relatives the greatest possible independence and psychical comfort, is induced by several factors.

The number of factors and hierarchy of meaning will be different and personal. Although the earliest possible introduction of classes aimed at teaching spatial orientation and independent movement and the continuous stimulation, the development of mental, motor, and physical of a visually impaired children is the undeniably priority.

It is necessary to emphasize that there are no publications or studies which evidence how, in the subsequent years, children understand and master orientation. There are no scientific studies clearly stating which competencies in spatial orientation children between three and seven year old possess.

As early as 1939, J. Piaget stated that in his/her first years of life, the child is not able to take the perspective of another person: they view the word through a self-centered perspective. Everything that happens is because of them, the world begins with them. They are at a stage when they are only able to conceive the world through their own point of view (egocentric perception). The ability of children to take the point of view of another person shapes slowly.

In the second stage of their development, children can deal with reality, taking other points of view, and especially adopting the point of view of another person. This means that the child can determine the position of objects in relation to any reference point (an allocentric perception).

In the third stage of their development, the child can take the point of view of things.

This process of social maturation is called decentralization by Piaget.

The development of spatial orientation abilities of visually impaired children is probably linked to this process of decentralization, which allows objectification of the examined phenomena. The issue is the basis of separation of children's spatial orientation, and requires a methodology to shape the orientation from the point of view of the child, and not from an adult. This difference should be taken into account when designing orientation-teaching methodology for VIP children: one should adapt the way orientation information is provided to the self-centered point of view of VIP children.

Children's world view is different from adults'. The meaning they attach to space-related concepts can be different, e.g., a child distinguishes left from right, but this is not enough to communicate. From experience, (s)he knows that it is enough to rotate by 180° and everything is different. To cope with this situation, the child reasons on the level of concrete operations. (S)He must realize that the position of the object changes with the reference frame.

Children's spatial orientation has two reference frames: egocentric and allocentric (or geographic).

In the egocentric frame, the child is in the center, focused on him/herself, everything being centered around his/her own body. This corresponds to the pattern of self-world. On average, children function with an egocentric orientation until the age of nine. Egocentric orientation requires training at the micro level, and is used in a small space—tactile space. Training has to be specific, related to a particular situation (e.g., the action of drinking). We allow the child a great deal of independence and to elaborate of his/her own strategies. Warren [1] claimed that to "help your child is to convince him/her that (s)he does not need your help."

Another guideline should be to avoid the child getting used to being helped for he will start expecting assistance from his/her teacher in every difficult situation. It is thus necessary to show the way to the child, and not to do everything in his/her stead. The teacher's task is to help the child direct his/her attention to the external world.

If the child sets his/her attention upon the teacher, it is necessary to adopt the attitude of the child adopts: the teacher is the focus, and not the environment. Independence is favored by short, precise instructions and by explicitly instructing them to act independently.

Allocentric orientation aims to teach gradually the far space within the locomotion classes, and is associated with movement. This includes training in between daily activities. This is the second level of training, training at macro-level, transition from eating activity to fun. This macro-level is implemented with activities carried out at various positions within a common larger space (a large room for example).

The spatial implementation of activities is correlated to three basic questions of orientation:

1. Where am I?
2. What is my goal?
3. How can I achieve it?

Sighted persons, once they determine their spatial position, will pave the route and will not have any issue with the execution of the navigation. A blind person determines where (s)he is located, shall specify the purpose, imagine an itinerary to reach the goal, but still has the difficulty of performing the task. Indeed, a VIP needs spatial imagination; (s)he must be able to mentally represent the planned journey. Indeed, the mental representation is a key element in the development of spatial imagination.

"Imagination is more important than knowledge, because while knowledge points to what it is, imagination points to what will be" (Albert Einstein). Imagination emerges naturally from ties between sensory-motor perception, emotions and memory.

It is possible to observe how the process unwinds by watching the reactions of children listening someone reading them a book:

1. The child is focused on listening: (s)he connects internal images and emotions with understanding;
2. When the adult finishes reading, the child will ask for him to read it again and again: (s)he needs consistency and stability to integrate images and to develop their imagination;

3. Then the child will tell the same story; his/her speech embodies the story in motion and sensation;
4. Finally, the child plays a story theatrically. The physical acting allows the child to understand the story with his own sensory perceptions.

The development of spatial imagination can be encouraged by asking children to imagine and narrate his/her own stories.

In the therapy, children are a special group, because of the possibility to initiate the development potential. Relevant stimuli cause the biggest changes in development and have the strongest impact in childhood; later, their importance greatly reduces, but the process of acquiring individual experience is still there.

The therapeutic practice contributes to the design of new technique level and tests to evaluate the child's development. However, even the best methods will not yield positive results, if they do not meet the basic psychological needs of the child, such as the need for familiar links, security, and for continuous presence of an adult. Satisfied psychological needs create facilitating conditions for the development of a structured sense of "me."

If the needs are not satisfied, it will result in accumulation of unpleasant experiences potentially leading to tension, guilt, a feeling of injustice, a lack of acceptance, expanding over defenses, and a tendency to develop a feeling of losing control over the environment, but above all, it will inhibit the development of the child's cognitive activity, which will limit the exploration capabilities and curiosity of the child thus potentially starting a pathological process. Lack of experience can cause a deformation of the person's self-image, leading to the formed self-image of a person helpless or to the inhibited development of the autonomy; this latter has a close relationship with the child's cognitive development. Therapeutic work is a specific emotional and intellectual relationship between an adult and a child.

The child, if treated as a subject, will find the conditions for proper development, including the development of the structure of "I." This is an important premise that affects the processes of learning and socialization.

Every child is different and requires different interactions. There is a difference between teaching a congenitally blind child and late blind one who was able to move independently for a time, and can refer to this experience and the memories it produced. The congenitally blind children will have more difficulty understanding the (spatial) concepts and may have different idea of space. Learning spatial orientation dependents also on the degree of blindness and of the occurrence of visual impairment.

An important task for the therapist is to prepare rehabilitation program adapted to the child's, with the ability to record the changes taking place because of the regular classes. It is important that members of the therapeutic team closely cooperate in the exchange of experiences, to continuously consolidate the acquired skills in a various situations, including the family environment of the child.

An individualized therapy plan should include:

- information about the child and pedagogical records,
- analysis of medical, psychological and pedagogical records,

- a collection of information from parents and guardians,
- analysis of the child's life, including the assessment of his living situation (e.g. type of parents' attitudes toward the child).

It is possible to design your own research tools, e.g.,

1. Daily clock—parents register the child's daily activities and their temporal occurrence; for older child it is possible to register data through the child's dream games.
2. The weekly "bank activities"—this register includes the child's planned and also effectively carried on activities during the week. An analysis carried out with parents' participation can allow for more insightful conclusions (e.g., the child's life is too poor, monotonous, or vice versa, the child's life overflows excess of classes, running between lessons music, languages, swimming pool, and others at the expense of leisure and welfare).
3. Develop a sheet of skills mastered and of these which should be taught to the child.

The efficiency of the used tool should be assessed with the following criteria:

- the child's interactions with his/her parents, with adults and with other children;
- the degree of physical involvement and environmental curiosity, and the extent of autonomy of actions;
- the posture, the transitions actions (sitting down and standing up), the movements, the coordination, the precision of movements;
- the orientation in a familiar environment, e.g., the child's room;
- identified habits and preferences of the child (what (s)he likes, what he/she does not);
- the objectives for child's needs and their priorities;
- the easiness to establish a contact with the child and to build emotional ties;
- the use of various methods of work, with a relaxed approach of learning.

Identified tasks and skills to be learnt must be clearly identified, and the child should focus on them and reach the goal. Skills development needs to be based on the already acquired knowledge. It is important to shape not only the verbal communication but also facial expressions, gestures, and changes in activity.

It is necessary to elaborate an approach which allows the child to know how to express what (s)he understands. The work style must be unified for everyone working with the child, parents included. A multisensory learning environment is fundamental, as well as the safety of the physical and mental health of the child. The family environment is a key element of the success; in order to favor the acceptance of the disability by child, psychological help and family therapy may be useful.

1.2 Range of Corrective and Compensatory Actions

A blind child should master a number of skills and knowledges, which are the basis for learning spatial orientation skills, e.g., independent and protected movement, assistance of a guide, or usage of a white cane.

The skills which should be developed are the following:

1. knowledge of the capacities of their own body,
2. sensory and kinesthetic learning,
3. sensory memory,
4. stability of the object,
5. sense of distance,
6. efficient detection of obstacles.

Knowing one's own body leads to the formation of self-identity, self-isolation from the environment. A man (women) must feel and know his (her) own body, its components and capabilities. This knowledge emerges around the age of three. Main stages of this knowledge's development are the following: perception of your own body as a whole, naming of body parts and knowledge of their role and possibilities during interactions, and consciousness of the possibility to control our body, its movements, and, as a result, our own behavior.

Kinesthetic and sensory trainings are designed to teach the correct understanding and interpretation of sensory information extracted from the environment and one's own body. This is, once again, an opportunity to analyze thoughts, emotions, and mentally pictured space when moving. Neurosciences provide a set of practical exercises for kinesthetic and sensory trainings.

The main component of the experience is the sensory system, or more precisely, the information acquired through it. The stimulations are generated by the environment (and perceived by our eyes, ears, taste buds, touch mechanoreceptors) and by the inside of the body.

Our senses begin to develop in the first two months of fetal life. When we think of our sensory organs, we consider the five main senses: hearing, smell, taste, touch, vision; all of them contribute to the development of balance and to the perception of gravity, all of them allow us to develop our perception of the world.

Later, in order to obtain a stable and structured perception of our environment, data from all senses are combined in complex sensory images. As babies touch everything in their environment, they learn the dimensions, area. Much later, around the age of eight months, a true visual image appears. Touch is very important for vision.

Psychologists compare touch actions of VIPs with visual actions of sighted people; they highlight the significant differences in the efficiency of one and the other way of learning. However, a synthesis of the touch data, which are analytical and synthetic, gives "a picture" that can be related to visual observations.

The first sensory system that fully develops during the fifth month of fetal life, the vestibular system, controls the sense of movement and balance. This system is in charge of maintaining static balance, which refers to information to knowing and keeping the body's equilibrium in absence of movement and is also responsible for dynamic equilibrium, i.e., maintaining the body's position in response to sudden movements (acceleration, release, upheaval). From birth to the fifteenth month of life, the vestibular system is very active. It stimulates every movement of the child. The movement activates the relationship between the vestibular and brain cortex. This is very important for the learning process. If we do not move, the vestibular system is inactive, we do not receive information from the environment. Starting with the knee-jerk reactions at the birth, the baby during the first year of his life learns a lot (standing, walking, running, etc.) taking into account gravity. Later, (s) he learns a range of activities like any sighted child: walking up the stairs, overcoming obstacles in the playground, etc., activities that require a good sense of balance.

For visually impaired children, it is advisable to avoid restrictions (e.g., riding a scooter or a tricycles, skateboarding). Such activities allow for contact with the ground, provide joy, show that (s)he is the same as sighted peers. Kinesthetic training is of great importance for the orientation. The term "kinesthetic sense" is understood as the efficiency of the control of muscle and limb movement in relation to the body, and other points of reference. VIPs have mobility issues of various types (uncertain walking, lack of coordination, reduced efficiency of movements, etc.). Furthermore, the plotting of airborne figures, on a horizontal or vertical plane, maintaining their hand in the same position, or rotating it by 90° are of major difficulties for VIPs. The aim of the training program is to teach the most appropriate, time effective and precise movements. The exercises may consist in carrying out controlled movements, in any settings, and performing simple manual movements, relevant to a given situation.

The implemented exercises could consist in writing in a plane or performing specific movements in the air, e.g., following the shape of geometric figures. Such exercises improve the efficiency of maintaining the width, height, and arches while using the white cane. This would allow for independent rotations of 90° and 180°, and also help maintaining the same stride length when walking, in order to obtain a smooth gait and a relaxed posture. Exercises of equal length step can be implement using tiles distributed in a room, or by going up and down using the stairs.

1.3 Touch Sense

The skin is the biggest organ of the body. It is filled with various mechanoreceptors reacting to variations in pressure, temperature, pain, etc. These information will allow the brain to decide whether or not to change the body's position.

The feeling to be touched increases the activity of the nervous system.

The lack of the touch may reduce the human motor capability and may affect mental health. Touch immediately after birth stimulates the sensory nerves' ends. If the nerves ends are not activated, the stimulation of the cortex decreases, leading to impaired muscle development, impaired sensory perception, emotional disturbances, and learning difficulties. The insufficient development of touch can inhibit the growth of nerves to such extent that it can lead to impairment of the vital functions of the body. The touch, even negative one (e.g., beating or flip), is preferred over the lack of the touch. Touch contact is a natural and integral part of life. The touch training starts at birth.

Training of touch can be based on the performance of the passive exercises and active babies from the first month of life. Different exercises are proposed in "Training Baby" by Edward Franus and Barbara Franus-Urbanczyk. These are passive exercises intended for the infant from the first months of life, and they prepare and develop physical skills in the following months. The exercises are natural, simple, and attractive to the babies. They are very well adapted to the various phases of child development and progresses of motor development, and include the psychic contact with the child.

The medical approach to spatial orientation via touch includes differentiation of textures, search for touch similarities and dissimilarities. The training uses everyday objects. A direct touch is predominant; it is advisable to build the ranks according to the specified criterion, e.g. roughness, hardness, etc.

The next stage includes exercises of object recognition and identification from tactile perception. The perimeter touch technique is the usual approach: it consists in exploring objects with fingertips, and includes several exercises to prepare for learning Braille.

The second technique, named "cartographic grid" is used situationally, e.g., when searching for dropped objects, when exploring unknown spaces (rooms, apartment, etc.). Gradually, object recognition techniques involving all body parts via touch are introduced; e.g., recognition of the ground's texture with the feet, comparing his/her height with another person, measuring the length of a feet, measuring the ulna length, etc.

In the next stage we start "training the indirect touch." These techniques allow to recognize (and thus to acquire the knowledge of) an object using another object held in the hand (such as cane for children). Children touch objects, analyze their experience, and recognize the object they touched indirectly. These exercises prepare to properly use the white cane and train them to efficiently receive tactile stimuli through an "extended hand."

1.4 Hearing Sense

The fetus moves spontaneously from the twelfth week. It is surrounded by the first models of sounds, which are the mother's heartbeat, her breathing and her voice. In the fifth month, (s)he reacts to the phonemes of the language spoken by the mother. After birth, the sense of hearing of a newborn is very accurate and important, as it is his/her first line of defense. The child will react to the sound of an unknown source, especially if it is loud and violent, by screaming in order to call for help. Throughout our life, hearing maintains vigilance of our brain to sort incoming content.

Hearing carries information important for safety. The interpretation of environmental stimuli by the VIP is extremely important in the orientation of the surrounding world. Auditory training includes exercises to locate sound sources, differentiation of sounds' intensity and interpretation of sounds' content. The ability to define and differentiate sounds is most useful for the purpose of orientation. It is important to distinguish the sound signals generated by the ground and transmitted by the white cane. Exercises are made using natural sources of sound and recorded sound situations.

1.5 Smell Sense

The sense of smell is excellent at birth. Sixth weeks old babies can distinguish between the smell of the mother's breast with the scent of another.

Smell is associated with memory and plays an important role in learning in infancy and throughout life.

Smell is also used to warn against dangers.

1.6 Sense of Taste

Taste receptors are located in the taste buds on the tongue. The range of taste sensations is between bitter, salty, sour, and sweet. Mouthfeel arise after irritation stimuli (e.g., with food).

It is necessary to be careful with children, especially at a time when they put various items in their mouths, which has the largest collection of touch receptors, in order to recognize them. Indeed, objects may have adverse effects (e.g., chemicals, drugs) or may cause injury to the child's mouth and to surrounding areas.

Tasting allows you to explore foods, fruits. Training the taste is important while learning activities of the everyday life.

1.7 Some General Comments

1.7.1 Memory of Senses

Our senses are largely dependent on memory.

The basic memory patterns are formed when we use our senses and the more efficiently we learn to use them, the more we are able discriminate very close stimuli values. Well trained senses allow us to experience our surroundings better and faster. The memory is a free system which facilitates the retrieval of data from all the areas of the brain. Therefore, in order to remember something as precisely as possible, it is best to combine physical sensations, sensory and emotional stimulations. The term "sensory memory" is a theoretical construct, but useful and used to determine the efficiency of memorizing specific sensory information, which acts as clues and landmarks for spatial knowledge.

Based on these data, the VIP will be able to maintain or adjust his/her orientation in the environment. (S)He associates the audio, tactile, olfactory, and kinesthetic information with specific situations, places, conditions, etc., which act as orientation cues. Training sensory memory will include a range of specific messages to master, e.g., the memorizing of specific sound signals generated by the environment, identifying known places, localizing objects in the environment (thus allowing for their recognition by touch) and will allow to identify the differences between two places. The auditory, olfactory and tactile information, combined with the knowledge of the position of fixed points where information is generated (or is available), assist the understanding and interpretation of spatial differences in different temporal conditions (such as weather conditions).

1.7.2 Stability of Objects

Object stability is linked to conceptual learning. This means that the general rules remain unchanged, regardless of the changes in the environment. If a VIP, who recognized a chair with his/her fingertips when the chair was located in the corner of the room, cannot identify the chair with the cane, if the same chair is located by the window, this means that the VIP has perceived the latter information as different, and this situation needs correction. Formed ideas are wrong, the received data induced a one-dimensional image based on the sensor data from one analyzer (one sense).

We must teach VIP to perceive the invariability of the object independently of their spatial context and changing spatial relationships. This knowledge is related to multisensory perception of the subject, i.e., object recognition through multiple senses. Data provided by different senses are heterogeneous. After the training, just one information is necessary to identify the object, but also a change of one of the characteristics will attest to the fact that we are dealing with another object. The VIP is taught to recognize one object thanks the heterogeneous data it provides and to categorize and to classify the cognizable objects.

Regardless of its position, the VIP using multimodal knowledge of this subject, should allow its recognition. For young children, the situation is even more difficult, e.g., young children did not yet developed the concept of mass. If we use the same quantity of plasticine to make a ball and a cylinder, and if we ask a child: where is more plasticine, the child will answer according to the length of the object (i.e., (s) he will say "cylinder"). It is only after their seven-eight years, that child can answer this question correctly.

1.7.3 Sense of Distance and the Notion of Ego-Motion

The concept of distance refers to the capacity to perceive spatial relationships between objects. Having a sense of distance means that the object is located in the nearby space, and some distance separates us from it.

A distance can be measured in usual metric units, or a number of steps between us and the object, if the object is not directly within our reach.

The concept of movement refers to our ability of noticing changes in body position in relation to any point in space. This requires to realize that either something is moving toward me or I am moving with respect to a specified fixed object.

The teaching of ego-motion perception starts from a situation where the VIP is close to an object, e.g., a wall. Next, a set of various items, located either close or far away, yet still within, are introduced to be directly grasped by the VIP. Through touch, the VIP estimates directly his/her distance from the object.

Exercises for distance evaluation using hearing cues start in a closed room. The VIP compares the distance separating him/her from the source of sound thus manipulating the concepts of "closer" and "farer." In the open space, the VIP uses natural sounds, e.g., the noise of the street traffic or the noise of the streets intersection in order to localize and orient in the space.

1.7.4 Sense of Obstacles (Mass)

Literature proposes many theories on how to deal with obstacles. Dolański [2], suggests that the VIP receives acoustic waves reflected from obstacles in the form of touch. Other authors emphasize that the sense of obstacles may be acquired through learning using appropriate techniques.

In practice, several exercises are implemented using movable obstacles and the trial and error methodology. Exercises are executed in both indoor and outdoor spaces. The VIP is told that his/her specific route, on which (s)he practice, may have obstacles. The VIP repeatedly wanders through the route, and stops when an obstacle is detected. The obstacles' layout changes several times during the training session.

2 Selected Methodological Topics: Work with a Visually Impaired Child

2.1 Games and Fun

"In the early years of child development fun is almost identical with real life. Having fun is in second most important need after the need to be fed, protected and loved. It is also an essential component of physical, intellectual, social and emotional development" [3, 4].

While playing, a child learns the world and how it is organized. Between the age of 2 and 5 children are at an important stage of their cognitive development, because (s)he learns to process information and to expand it in the work. Interactive communication and fun with his/her peers accelerates this development.

It should be noted that nowadays, children do not have the time or opportunity to play regularly without the necessary supervision and mediation of adults. The variety of games and their appeal should provide children a lot of joy and pleasure. Games should be selected according to child's needs, age, and level of fitness. Visually impaired children in their movements, games and making noise should not be unduly constrained by adults. Toys for blind children should be safe, attractive, and should emit sounds. Visually impaired children must learn more than sighted children.

The activity must be at the center of each game. It is necessary to show that behind a game there may be something better, more interesting. The variety of games, their nature, whether they are played solo or in a group, applies to all children. Fun child must be geared toward achieving the objective. Perception and coordination are developed by fun and physical activities, often combined with music, relaxation and controlled breathing.

It is important that the child follows the rhythm of the music, knows and executes the recommendations suggested by the songs. It is often better to give up the CD recordings and sing along with the children. Manipulating objects, building, playing with plasticine, and any other didactic play that will teach them to be self-sufficient when performing an action must be simulating and (auto-)correcting. Experience in working with children shows that excellent course of action is lying board games with your child. Each game is fun, and not every fun is a game.

Children's behaviors reflect the fun they are having during the playground and thematic plays. Thematic and building games should be implemented in parallel. Agreement in force in these pastimes refers to specific situations that the child is trying to play. A game can be played alone or in a group with other children. In group, one child plays a dominant role, and the others must respect his/her authority, otherwise a conflict may rise. In the case of games, all partners have the same chance to win and all must respect the predefined rules. A game is a situation of equal chance for all, a chance for competition, which requires effort and constant desire to achieve a goal. Success is built on the game's understanding and on anticipation. While playing, the child may learn more self-control, develop reflexes, orientation, speech, thinking memory, and interpersonal skills.

Bought board games are not recommended for blind children, because their instructions are too complicated and their charts illegible. Methodology for the construction of board games is tailored to the cognitive abilities of children from five to nine. Analysis of the rules of games with a child ensures his involvement and the games' adequation to his/her skills.

The construction of a game has several stages and each is accompanied by emotions.

The first stage (for the children of 5-9 year old) brings meaning to the game type "race." The game is dominated by an adult, but a child cannot loose. Each game should propose only one activity.

The second step shows how to build a story in game.

The third stage involves the construction of a variety of games; powerful mathematical and computer science tools may be helpful. The benefice of games is to improve the precision and efficiency of manual and intellectual skills resulting from the content of the game.

2.2 Relaxation Techniques

Relaxation is the elimination of negative emotions. The goal of relaxation for children is to relax muscles, to improve peripheral circulation, to abolish internal tensions, and to give the child a sense of calm. Relaxation technique by Jakobson [5] (in its modified version by B. Kaja) aims to carry out activities via loosening and tightening the muscles while having fun, which the author calls the "weak-man and strong-man" game.

Example: a child identifies him/herself with a small ant, relaxes muscles, then (s) he identifies with the big elephant, heavily straining muscles. Exercise should include all parts of the body: arms, legs, trunk, neck, and head. It is better if the relaxation of the children is in the supine position, which increases the feeling of safety.

Relaxation training based on autogenous Schultz approach [6] can be adapted to small children (cf. [7]). Children relax through different approaches, e.g., the listening of the story of tired Little Red Riding Hood, they identify themselves with the heroes of fairy tales, and make suggestions to the therapist. The story may be accompanied by a soft music. Children should be comfortable in a room devoid of additional incentives (such as a noise).

2.3 The Method of Sound Symbols (a Music Therapy)

The method is based on music and movement; it is suggested for children from 5 to 6 years old. Suggested activities are divided into different exercises ranging from mobility, providing awaking of the whole body, with voluntary movements, controlled movements and manual movements. Children move according to the rhythm of music, then they activate (via dancing or via running), then they stop suddenly in order to control the emerging setting.

Training of cognitive processes develops thought processes. Those exercises will help the child to notice the characteristics of a sound (low/high, short/long, quiet/loud), and link them to some symbols (abstract knowledge).

Those exercises can also help to recover from emotional tension; this training is a combination of speech, music, and movement, and may use poetry too. It is also possible to use fairy tales illustrated musically, and apply them later to staging exercises or pantomime.

2.4 Method Based on Painting

The method of painting with fingers has therapeutic values, and relies upon the tendency of children to dip their fingers in substances with the consistency of mud. The substance (paint) should be in cups adjusted to the size of a child's hand. (S)He paints on sheets spread on easels or tables with access from each side. Children can paint on any subject, and inform the adults once (s)he completed his/her work, then talk about its content. An additional advantage is to sensitize fingertips, essential for the exercise of touch of a blind child.

2.5 Drawing

Drawing and painting are human natural means of expression and communication, in a similar way as talking, singing or gestures. Blind child can develop these means of expression if they are offered the relevant technical possibilities to draw and to control their work by touch feedback. Drawing is a common way to communicate information, it is a language in itself.

For a visually impaired child the apprehension of the shapes of objects and the identification of relationships between linking these objects directly, from the touch feedback, are very difficult tasks. Therefore, it is necessary to perform exercises exploiting the concept of a spatial plane. This includes not only drawing and analysis of drawings, but also, and perhaps above all, exercise aiming the apprehension of orientation in a small space. Learning and consolidating concepts of spatial relationships in a small space is a prerequisite for proper understanding of the concepts and spatial relationships in a large space.

2.6 Maps in Relief

Relief maps facilitate the movement of VIP and are an important working tool for professionals in spatial orientation. They provide knowledge about the environment, and allow to learn concepts, spatial relationships and spatial configuration of specific areas. Maps, plans, diagrams, and sketches are useful at every step, in every area of life and every level of education.

Visually impaired people have a hard time accessing and learning how to process information from maps and charts used in everyday life. In Poland, the tyflo carthographic versions of maps were in beta-tests for many years in order to assess their quality; teachers themselves usually made copies of maps in relief for their own purpose. Often teachers benefited from the relief maps produced in Germany. In 1987 the Polish Association of the Blind initiated the production of relief maps using the vacuum technique (rather expensive), leading to maps with a static content. The next step of mapping technology was based on a matrix in order to obtain the protrusions needed to touch stimulations. In 2003 the Centre for Blind Children in Owińska implemented a tyflographic program (professors Alina Talugder and Marek Jakubowski) for accommodating the educational needs of blind people. Electronic matrix for maps display was realized; its originality comes from the possibility to modify the map content dynamically.

This new technological approach allowed to elaborate maps of various spatial precision (possibility of "zooming"). Therefore, tactile maps can be adapted to various needs and to the touch stimulation perception of different end users; it is also possible to adjust the contents of the map, i.e., increase or decrease the amount of details.

The advantage of the above solution is the easiness of creating such map and the possibility to exchange those maps in electronic form between the institutions involved in teaching VIPs.

The spatial orientation classes include the preparation of outlines, plans, maps, hand-made foils, relief or Braille maps of a particular route. Often this is done with the student setting his/her own landmarks and information. In order to start to learn spatial organization, children can create a topographical map of a room or a building.

It is also possible to use dedicated heating devices to highlight any content, drawings and maps or to use the "inflating paper" (paper capsule, manufactured in Norway, Fig. 1); under high temperature, the black parts of the sheets (colored with a special pencil) will increase their in volume, swelling and forming bulges.

2.7 *The Method of Developing Movement*

Movement is a developmental factor but also a mean to treat developmental disorders.

The method presented here was defined by Sherborne [8] and is derived from the concept of Laban [9], who believed that knowledge of one's own body is of a great importance in building relationships between people, gives a sense of security, and enables the recognition of space, where the child is located.

Sherborn's method is based on the natural needs of the child to establish close physical and emotional contact with parents (called romping). The basic aims of this method is to develop body awareness through movements and improving

Fig. 1 Map used during the orientation class (adapted from TyflowySwiat [11])

mobility, and spatial awareness, especially to detect if other people are present inside the same space in order to communicate with them. More than just motion, this method helps developing other important elements such as the analysis of kinesthetic sensations, the feeling of balance and provides also tactile sensations to the VIPs.

When the child meets other persons while exploring, the known space becomes more familiar, safer, allowing the child be more active and creative. Different categories of movements can be developed: the movements leading to the knowledge of your own body, movements to help shaping the relationship with the physical environment, movements leading to the formation of interactions and connections with another human being, movements leading to teamwork, and the creative movements.

2.8 Brain Gym

The “brain gym” is a study of blood’s circulation. Masters of applied kinesiology Alexander, Rudolf Laban, and Milton Traeger proposed this method [10].

Brain Gym is a system of mind–body integration which uses brain gymnastics to strengthen bilateral functions and skills in the middle of the brain, where both hemispheres work together.

Student assimilates the experience of both hemispheres. Assumptions of educational kinesiology are the following:

- the whole body is ready to learn
- physical exercise stimulates brain functions
- stress inhibits learning.

When under stress, the mind-body's activity is focused on preparing the fight or a response during the fight (aggression or anxiety). As a result, the memory is locked and abstract thinking and reasoning are significantly inhibited.

Kinesiology exercises are done easily due to their naturalness; with a little effort, exercises give a feeling of satisfaction. Exercises are divided into four groups:

- movements, which allow to cross the center line (they stimulate both large and small motor skills);
- muscles stretching exercises (they tell the brain that the person is relaxed, calm and ready to go);
- energizing exercises (they provide the necessary speed and intensity to the neural processes);
- exercises to train your attitude (they lead to a deep positive attitude or affect the emotional limbic system of the brain which interacts with the centers of perception of ourself).

2.9 Kinetic Therapy—Treatment of Movement

Movements and exercises, as natural stimuli, can affect the body, contributing positively to the activities of all organs and can thus increase or restore physical fitness. Therapeutic exercises are conducted by specialists during physical therapy while also teaching techniques to caregivers and parents, are very important considering their privileged relationship to the children.

Exercises are divided into:

- local exercises (e.g., impacting on specific groups of muscles or increasing a given range of motions);
- exercises improving overall fitness (they aim to improve the overall physical performance or relaxation);
- passive exercises (performed by the therapist);
- active exercises (performed under the direction of, or with the help of a therapist);
- specific exercises (e.g., breathing, coordination, and relaxing exercises);
- compensatory gymnastics (a resource of exercises that compensate for quantitative and qualitative impairments of movement);
- corrective exercises which are intended to improve what has been damaged, (e.g., improving posture).

3 Conclusion

The system of education in the field of spatial orientation is based on the use of the possibilities inherent to human body. You have to learn the skills of learning and the joy of learning.

The purpose of corrective and compensatory training is for the VIP to explore the world the world and function in it without vision but through touch. This new mechanism is very different than how sighted people explore the world (which is 90% based on sight), but certainly not worse.

The teachers of spatial orientation create and organize the learning process, and their personality; they play a very important role in the success of the training program. The training can be fully individualized, and will involve alongside the child's development to match his abilities and needs. The training program is based on daily life and specific situations. A progressive inclusion of well selected concepts will facilitate the acquisition of information our various senses. Recalls must be accompanied by the fixing of meaning and an experience of emotions. Children need move, play and exercise a lot; letting them experience freely, stimulating their curiosity, and directing their attention to the surroundings is paramount.

It is necessary to gradually guide children and replace the conventional techniques of sighted people by techniques of spatial orientation adapted to their disability, e.g., accompanying the child (traveling with a guide), protecting them with specific equipment when they travel autonomously, and providing them with techniques to look for dropped items.

Since the beginning of classes of spatial orientation it is mandatory to associate the "concept of cane" and the cane. The introduction to the cane techniques is dependent on the physical and mental readiness of the child (individual decision made when they are around 10 years old). Operating the white cane as a natural extension "of touch in space ahead" provides the ability to collect information, safely and to produce efficient self-movements.

Learning Braille is very important as one of the factors important for the independency of VIP. The system, developed in 1825 by a blind Frenchman Louis Braille, is now adopted universally and has been applied to all the languages of the world.

It is necessary to emphasize the needs to learn a personal signature - skills acquired on the basis of muscle memory.

The training of a guide-dog is based on the spatial orientation of a VIP. The VIP thinks and decides, and must have imagined the itinerary in his mind. The purpose of a guide-dog is to identify and to avoid obstacles. It is important that a VIP moving with the dog completed the spatial orientation training and has always with him a white folding cane, which is used situationally, e.g., when boarding a train. The guide-dog can be obtained at the age of sixteen.

These learnt skills can be used in any situation. In addition to the traditional models of space learning, modern techniques of education, innovation and new technologies are introduced, e.g., a computer network, internet, and software support. Educating the VIP to always stay up to date on the new technologies developed to compensate for their handicap will increase their learning opportunities, and, in adulthood, their job opportunities in real companies.

The quantity and quality of assistance provided to the VIP will greatly facilitate their everyday activities. Various assistive systems are developed to support space learning; some of them are obstacle detectors or verbal guidance systems (e.g., about the passed-near-by the building). Several experiments with robots as guide for VIP are also conducted.

Taking the responsibility to teach VIP children requires high qualifications and adequate preparation. Methods evolve continuously and adapt to evolution in our understanding of how we process space.

Acknowledgements This chapter is dedicated to my outstanding student and friend Miss Hanna Pasterny. Hanna Pasterny is a graduate of Romance Philology and postgraduate in speech therapy. She works as a consultant for persons with disabilities in the association "Civil Initiative Development Centre (CRIS)" in Rybnik (Poland). She is a social assistant for the European deputy Prof. Jerzy Buzek, and a volunteer at the Association for Welfare of Deafblind. In 2009, Hanna received Lady D award for her involvement in social integration of the VIP, and in 2011 she was awarded the distinction "Man without barriers." Hanna has authored three books "How I conquered Belgium with the white cane" "Tandem and tartan" and "My travels in the darkness" (all written in Polish).

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Scene Representation for Mobility of the Visually Impaired

Guillaume Tatur

1 Introduction

As it is significantly correlated with autonomy and quality of life, a vast majority of the developed approaches or devices dedicated to visually impaired individuals attempt to augment or support orientation and mobility abilities and maximize independence, safety and efficiency of movement [1]. Experience gained from sensory supplementation studies, visual neuro-prostheses experiments and technical aids development provide evidences regarding some general guidelines for scene representation design at a functional level, whether it address the problematic of mobility or another task:

- User's impairment: should the user suffer from congenital blindness, late blindness or low vision, the scene representation should be adapted,
- User's functional vision (i.e., efficiency of use of the remaining visual information which, among other things, depends on the visual strategies learned or developed) and abilities,
- The device itself (e.g., tactile stimulation device, retinal implant, etc.), through which the representation is provided,
- The complexity or richness of the information that can be conveyed through this support,
- The sensory modality (or modalities) that will receive the information,
- The defined objective(s) of the representation.

For this last point, we can distinguish two approaches regarding the category of information that a representation may provide. The first approach would be the attempt of representing a scene using general information (e.g., raw input from a

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camera), expecting that the user will extract the relevant cues for the current task performed from the pattern of luminosity values as represented by the image pixels gray level for instance. This approach is highly dependent on the complexity of the represented information and on the user capability to decipher this ambiguous representation through the selected sensory modality. Another approach would be to optimize a representation to provide specific information for a particular task like mobility.

Optimizing representation regarding a specific task or activity is interesting for several reasons:

- It takes into account the limited capabilities or resolution of the device,
- Information can be filtered or simplified and enhanced relatively to the task performed,
- As it is designed for a specific task and as it uses specialized information, this representation should be easier to understand.

Additionally, a representation that requires too much time and effort even after training may obviously be detrimental to a safe and efficient navigation. Mobility is a time-critical activity where one should be able to understand the environment (e.g., spatial layout of the surrounding environment) as well as to anticipate and adapt to its dynamic.

The complexity of designing such representation may be partly attributed to the fact that one needs to deal with some generalized–specialized balance. Indeed, as stated above, designing an enhanced representation dedicated to a complex task such as mobility requires that the system provide a balanced amount of specialized information as well as general information of the scene. As an example of specialized information, a representation may give access to the distances to obstacles in the scene through a simple coding of these distances into artificial stimuli intensity. This simplified representation may be easier to understand and to decipher. Additionally it will certainly be very pertinent for a safe perambulation and allow the user to safely and efficiently move through an environment and to avoid obstacles. On the contrary, a representation based on general information may for instance give access to luminosity information. This representation may be ambiguous and unstable regarding several factors (e.g., lighting condition, viewpoint, textures), it might thus require more time and cognitive effort to be processed. However, it may allow the user to infer the location of distant and visually salient scene features (e.g., ceiling lights, large contrasted walls) and use them as landmarks for navigation.

In the following sections we will present an overview of currently proposed scene representations for the visually impaired. As stated above, we can distinguish different kind of visual impairments, from congenital blindness to low vision, and thus different needs and abilities. For each, several approaches and technical solutions have been proposed or are still in development.

One can note that a same technical aid can be used in several type of visual impairment as for instance an electronic cane or a BrainPort, presented in the following section of this chapter, may be used either by blind persons or by individuals suffering from low vision. However, some scene representations and technical solutions are intrinsically dependent on the visual impairment they are dealing with and the chosen sensory modality for information presentation. In the following sections we will thus review these approaches and present the related methods for scene representation.

2 Technical Aid and Sensory Supplementations Systems

In this section we will present non-invasive technological solutions in order to give some information to the user about its surrounding and mobility related information based on sensory supplementations systems.

In these systems, information usually acquired from one sensory modality are captured through an artificial sensor (e.g., video camera) and are transformed in order to create stimuli adapted to another modality. We can distinguish two main categories of these devices in order to supplement the sense of vision: visuo-tactile and visuo-auditory systems.

2.1 Visuo-Tactile Sensory Supplementation

The objective of these devices is to convert visual information into tactile stimuli. A large literature exists on this approach and confirms its efficiency in order to give the user, after adapted training, the ability to recognize simple geometric shapes [2, 3], to localize entities [4] as well as the ability to estimate other vision related information such as distance and perspective [5].

As stated in the introduction, this technique is dependent on the stimulation method as several limitations will apply (e.g., maximum signal frequency, required stimulation signal intensity) as discussed for instance in [6]. The principal stimulation methods are electrotactile and vibrotactile. Electrotactile stimulations are based on a direct electrical stimulation applied on the skin whereas vibrotactile stimulation uses localized vibrations to elicit sensations. Additionally, it is noteworthy that the location of the stimulation on the skin will constrain the maximum allowed spatial resolution that can be perceived although some authors argue that the poor tactile (two-point) resolution of the skin may not be the limiting factor in perceiving complex images for instance as the brain extracts information based on the stimulation patterns [7].

Various systems have been proposed so far and we will present some of the most representative.

The Bach-y-Rita's TVSS (tactile vision substitution system [7]) is one of the early developed and most well-known visual to tactile sensory supplementation devices. The system converts an image captured by a video camera in order to generate tactile

Fig. 1 Young subject reproducing hand gesture perceived through a head-worn camera and a 6 × 24 vibrotactile array. The LED monitor in the foreground show the active pattern of the tactile display. From Bach-y-Rita et al

stimuli through a stimulation device placed on some part of the skin such as the lower back, the abdomen or the fingertip in the first version of the system.

The proposed scene representation was a point-for-point projection of scene images, captured by a fixed, hand-held or head-worn camera (Fig. 1). Images were transformed into black and white images and reduced spatially to accommodate for device resolution onto a two dimensional tactile stimulation matrix (between 100 and 1032 stimulation points).

In [8], extending the work initiated with Bach-y-Rita, Collins et al. have developed a 1024 wearable electrotactile system placed on the abdomen and converting images acquired through a 90° field of view camera to a point-to-point electrical stimulation pattern. As a result, subjects equipped with such device (Fig. 2) have been able to safely avoid and navigate around large and contrasted objects such as tables and chairs. However, these results are only valid in simple indoor environment as subjects, even trained, failed to use the system in real outdoor environment (see also [4]).

This setup, which gives the user the possibility to experience and analyze the dynamical scene, was later modified into a tongue display unit (TDU, Fig. 3), also called BrainPort [9] that allows reduced required electrical current for the stimulation and was more suitable for mobility purpose.

In [10], the authors was evaluating if the use of a BrainPort influenced subjects ability to navigate a standardized indoor course composed of highly contrasted

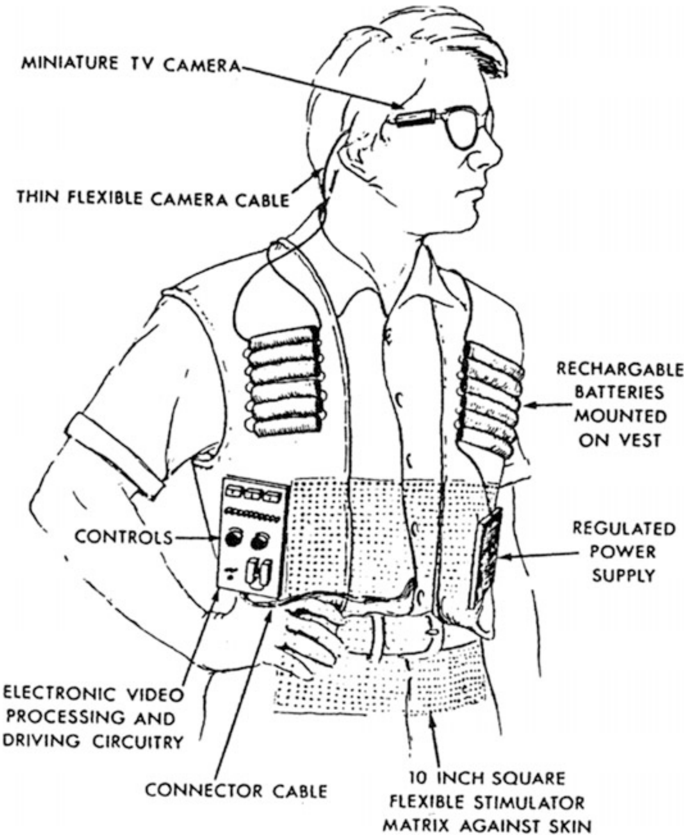


Fig. 2 A 1024 wearable electrotactile system. Images are captured from a head-worn miniature camera and are reduced to match the device resolution. Corresponding gray levels of this reduced image will drive the electrical stimulation amplitude on the abdomen. From Collins et al

obstacles. The experimental device was constituted of a tongue electrotactile stimulator (20 × 20 array of electrodes) and a spectacle frame mounted camera with a field of view of 73°. They found that the use of a BrainPort help subjects to avoid obstacles in such environment and this ability were also observed in other studies as in [11].

These devices are based on the general information approach presented and discussed in the introduction. Validity of this approach in the context of sensory supplementation systems and real world tasks have been discussed by some authors [4, 12].

Some research teams have developed a “specialized” representation approach in order to present relevant and adapted information for mobility.

In [13], the authors propose a novel scene representation method dedicated to mobility. In their approach, the 3D scene captured by a stereoscopic pair of

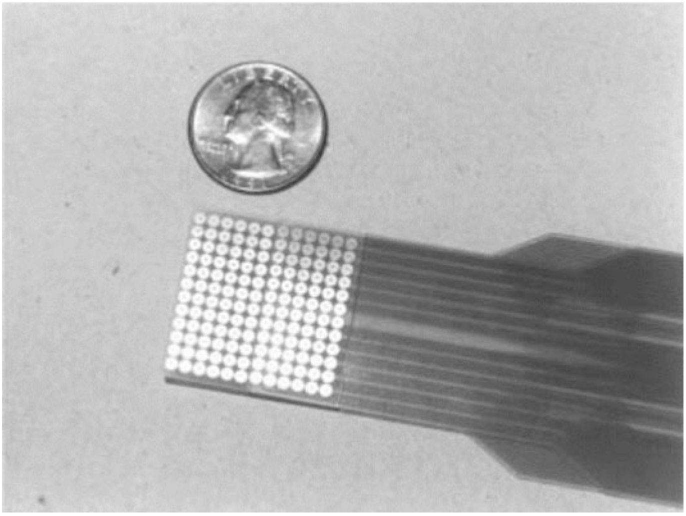


Fig. 3 A tongue display unit. Electrotactile stimuli are delivered to the tongue via flexible electrode arrays placed in the mouth. From Bach-y-Rita et al

cameras, is projected vertically (i.e., ground projected) on a 2D plan. Through the proposed processing, obstacles are represented as non-accessible areas on the plan, whether they are overhanging or lying on the ground. The obtained simplified map of the environment is then presented to the user through a hand-held touch stimulating Braille-like device [14] (Fig. 4) and is updated in real-time. In the proposed representation, processing of the 3D data allows a binary partitioning of the space into two zones: free path and obstacles. The system is aimed to provide a dynamical tactile representation of the scene where raised taxels (i.e., individual tactile stimulators that compose the device) principally show the limits of the obstacle-free space. Furthermore, information are represented on the tactile surface in a user-centered Euclidian reference frame which observation point is indicated by a notch on one of the border of the tactile surface. Preliminary navigation experiments in standardized test environments indicate that the system can be used to perceive the spatial layout of the dynamical environment through this binary tactile representation.

As another approach to mobility, Chekhchoukh et al. propose a guidance technique using also a TDU (Fig. 5). In [15], the authors mainly propose to simplify the scene by only showing, in a perspective view, a 3D path composed of dots that must be followed by the user for navigating from one place to another. Stimulus intensity associated to each dots represent the distance of this 3D dot from the user. The authors observed that a symbolic representation appears to be more easily understood.

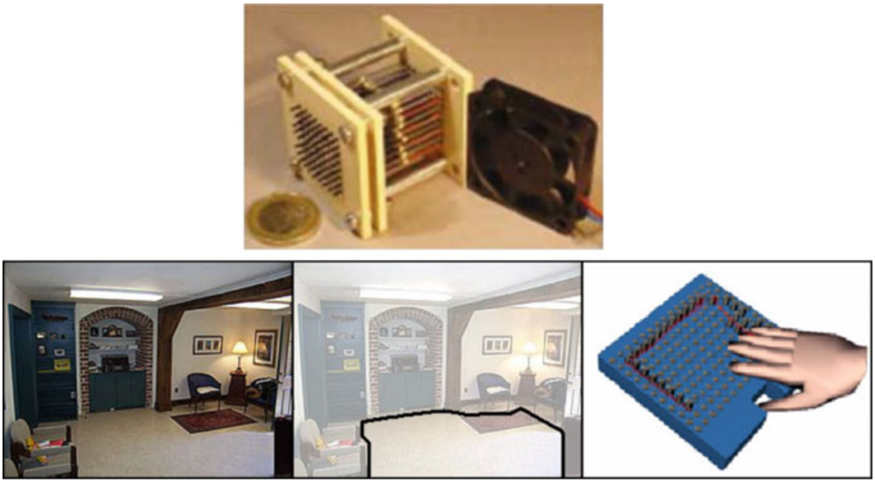


Fig. 4 Illustration of the developed scene representation (*bottom row*) and device (*upper row*). Image of the scene, acquired from a stereoscopic pair of cameras, are processed in order to create a 2D tactile map (*right image*). This simplified representation shows the accessible and non-accessible parts of the environment delimited by raised taxels. The center of the Euclidian reference frame is materialized by a notch in one of the device borders. The stimulation device is a Braille matrix of 8 by 8 shape memory alloys based taxels. From Pissaloux et al

2.2 *Visuo-auditory Sensory Supplementation*

Taking advantage of the human auditory system performances [16], visual to auditory sensory supplementation systems may be categorized into two approaches:

- The auditory coding of the position and distance of the obstacles through the use of an ultrasonic or laser rangefinder device for instance.
- A visual to sound online translation based on the coding of visual pattern extracted from captured images (e.g., from a head-mounted camera).

For the first category, the auditory feedback in such devices gives the user clues about the texture, the distance, the size, and the position of the scene entities. In these devices, distance is mainly represented by the sound intensity and the position around the user is coded through binaural disparity. A non-exhaustive but representative list of these devices is presented below.

- The C-5 laser cane [17] is a triangulation-based device, embedded in a white cane, that informs the user on the presence of the obstacles in mainly three zones:
  - UP (at head height to detect overhanging obstacles),
  - FORWARD (in front of the user as an extension of the cane tip),
  - DOWN (to detect obstacles on the ground, stairs and holes).

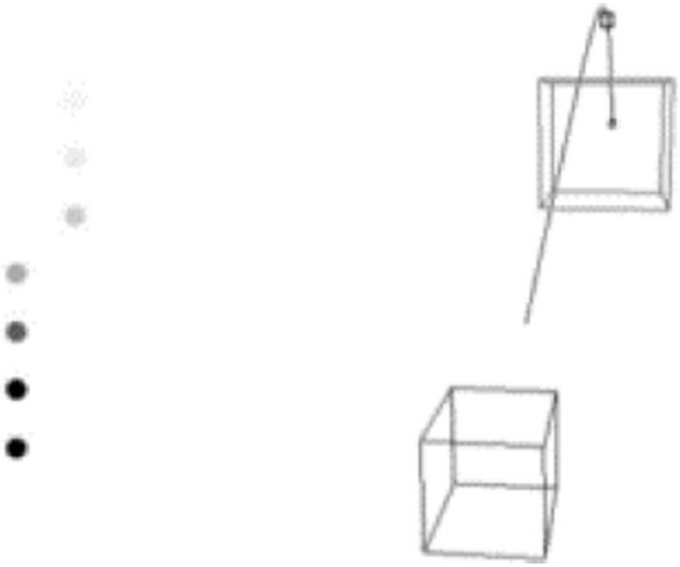


Fig. 5 Illustration of the proposed representation method from Chekhchoukh et al. *Left* illustration of the active electrodes on a 12 × 12 electrode array. *Shades of gray* represent stimulation intensity. *Right* perspective view of the 3D positions of two spatial locations. Navigation between places (*Right image*) can be achieved by following a 3D path. This path is composed of *dots* (*Left image*) perceived through the TDU as localized stimulation in a perspective viewpoint. Stimulation intensity depends of the distance of the 3D dots from the user and act as a guide to the destination location

Obstacle detection output provides information regarding the presence of an obstacle in each zone by the generation of a specific tone.

- The binaural sonic aid [18] is a wide (55°) beam ultrasonic rangefinder device mounted on a pair of glasses. In this system two receivers are placed on each side of the emitter. The signal from the receivers is adapted and presented to each ear separately, which allows large objects localization. Frequency of the generated sound signal is relative to the obstacle distance.
- The NavBelt is a computerized electronic travel aid using an array of ultrasonic rangefinders. This device has been presented in [19]. It uses a binaural feedback to guide the user toward an obstacle free direction of travel. An alternative "image" mode exists and provides the user with a 180° acoustic image of the environment based on instantaneous polar obstacle density measurements. Using a temporal sweeping technique [20] to present this acoustic image, the scene in front of the user is automatically scanned horizontally (left to right) and sound amplitude at a time t is driven by obstacle density in the corresponding direction.

- The Mowat Sensor, as described in [21], is a hand-held device equipped with an ultrasonic range finder. The distance information is transmitted by tactile vibration and vibration intensity is proportional to the proximity of the obstacle.

For the second category based on image to sound conversion, we will present the most representative approaches.

- The vOICe was developed by Meijer [22] and it proposes an image to sound mapping based on the conversion of the video frame pixel arrays into successive sound signals. Each signal is generated according to the pixel position and brightness: pitch is proportional to pixel height (vertical position), amplitude (loudness) to brightness. To give information on the horizontal position of the stimulus, a left to right scanning technique have been implemented ("synchronization" sound click indicate the start of a frame scan). The working resolution of the system composed of an audio headset and a head-mounted camera (Fig. 6) was of 64 × 64 pixels with 16 gray levels available per pixel and an image-to-sound conversion time (i.e., duration of one frame presentation) of about 1 s.
- Capelle et al. [23] propose a different approach: the PSVA system (Prosthesis Substituting Vision by Audition). Consisting of an audio headset and a head-mounted camera (Fig. 7), this device is an experimental prototype that uses a simplified model of the retina. Indeed, the system uses multiple resolution of an input image to process information in a similar way than the retina by distinguishing central and peripheral field of view. Information contained in

Fig. 6 The vOICe system from Meijer et al. The system is composed of a stereo headset and a head worn camera. *Right* individual using a portable version of the device while walking on a street

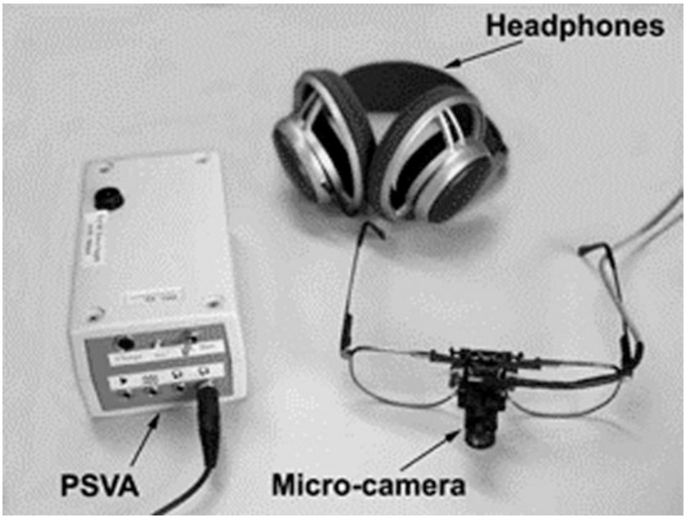


Fig. 7 PSVA system from Capelle et al.

each of these resolutions will be represented using different sets of tones. Finally, an inverse model of audition with an image-to-sound mapping based on a pixel-frequency association and binaural intensity balance is used to create the output audio signal.

- The See ColOr (Seeing Color with an Orchestra) Mobility aid was introduced by Bologna et al. [24]. They postulate that color and depth are important information for mobility as color allows detecting potential landmarks and depth can be used to evaluate the distance to objects in the scene. The authors approach was thus based on the sonification of the color and depth information. Color was represented by the Hue, Saturation and Brightness values parameters of the HSL color system and was associated respectively to an instrument timbre, sound pitch and sound mixing using double bass (for low luminosity levels) or a singing voice (for high luminosity levels). Color information of the video image is computed in real-time on a row of 25 pixels around the image center. Depth information coding is based on sound duration (e.g., 254 ms duration for distances between 1 and 2 m). As an experiment they have shown that both blind and blindfolded subjects successfully followed a colored path on the ground (Fig. 8). Additionally a well-trained subject was notably able to successfully perform simple tasks such as walking on a corridor and find a colored object or detect an open door.

Fig. 8 A blindfolded subject equipped with the See ColOr device composed of a stereoscopic pair of cameras and a stereo headset. Information from the cameras are processed by a laptop which delivers the sound signal allowing the subject to follow a colored (*red*) path. From Bologna et al.

3 Using Residual Vision: Augmented and Virtual Reality Devices

Several visual disorders such as retinitis pigmentosa (RP), age related macular degeneration (AMD) or glaucoma may induce severe vision loss. Indeed, persons suffering from low vision may experience significant visual field reduction (like in RP patients, Fig. 9) or central vision loss in the case of AMD for instance, visual defects (e.g., scotoma) and other visual impairments (e.g., reduced contrast sensitivity, impaired color vision).

Augmented and virtual reality devices make possible, to a certain extent, the compensation of these visual impairment by:

- Providing additional information in the remaining field of view. Without such technical aid, these information may not be directly accessible. For instance, in the case visual field reduction, laterally located static or moving obstacles may not be seen directly. The idea is thus to transmit alert signals or additional information in the residual field of view in order to facilitate acquisition of static and dynamic information of the environment.
- Enhancing the residual vision, by displaying reinforced contrasts and colors for instance.

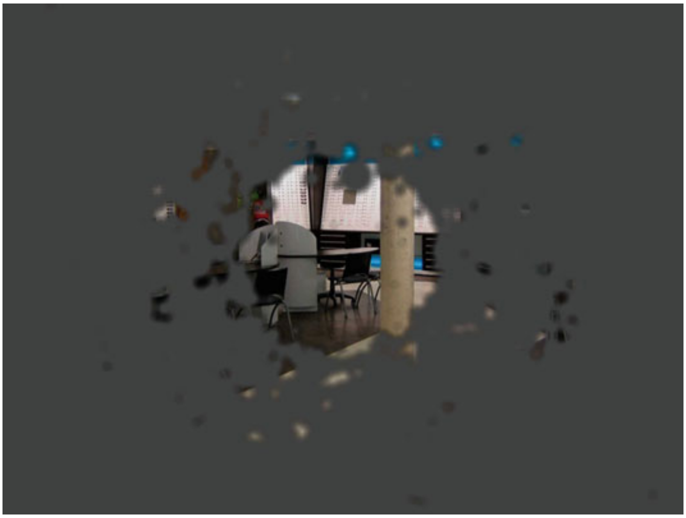


Fig. 9 Illustration of the residual visual field of an RP subject, characterized by a peripheral field loss (*dark gray areas*)

Fig. 10 Immersive and non-immersive devices. *Left* Lumus (Lumus Ltd) augmented realty device with see-through display screens. *Right* Vuzix (Vuzix Ltd) virtual reality device with opaque screens

These devices (Fig. 10) are composed of one or two displays, and may be non-immersive for augmented reality devices or immersive in the case of virtual reality devices.

Designing such technical aid for low vision persons is not an easy task as, for instance, there is a large interindividual variability in visually impaired residual vision and furthermore in their functional vision.

One of the most well-known methods based on augmented reality technique are from Eli Peli's Works. In [25], the author presents his approach on "vision multiplexing". Peli's approach is based on visual field restitution as visual field is one of the key components for mobility. The importance of visual field extent related to the quality of life and mobility of visually impaired individual is confirmed by other studies such as [26, 27].

The principle of vision multiplexing, in the case of persons with a severely restricted visual field of view [28], can mainly be described as a spatial multiplexing technique: using a wide- angle head-worn camera and a see-through head-mounted display, the method is based on the presentation of captured images contours (through real-time edge detection) displayed as white lines and superimposed on the natural view (Fig. 11). As the camera possess a wide field of view (from 75° to 100°), the contours are minified to match the smaller field of view of the user and thus provide additional information that would not or barely be accessible otherwise. It is noteworthy that without embedded eye tracking system, the user must keep his gaze at the same central position in order to maximize the visibility of the minified images.

In their experiments [29], the authors evaluated whether the device improved subjects performances in a visual search task. One can note that this ability is highly correlated with mobility performance [28]. Subjects, with a field of view extent ranging from 7° to 16°, have also been tested on an obstacle collision risk estimation task in a virtual environment. For the first experiment, using the device

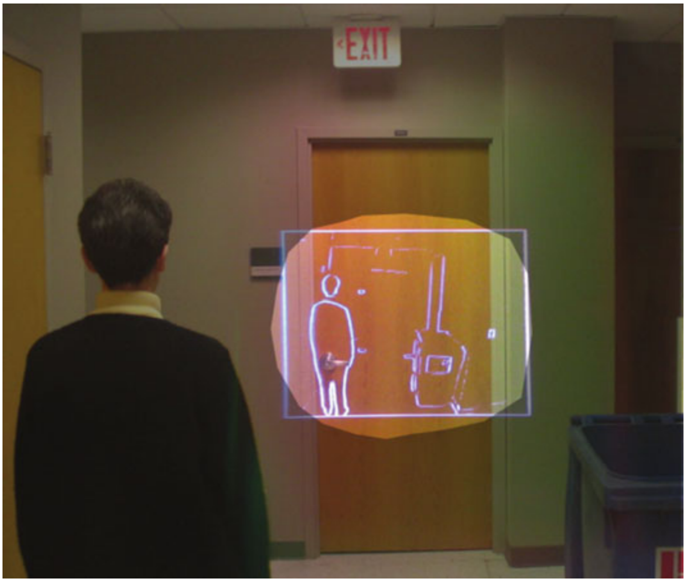


Fig. 11 Illustration of the spatial multiplexing principle dedicated to low vision patients with severe visual field reduction, equipped with a head-mounted display and a wide field of view camera. As it is a see-through device, the natural scene can be seen directly (*background image*). Edge maps are calculated in real-time from the captured camera images and are minified and displayed as white lines. Although the patient has a tunnel vision (illustrated as a *circular highlighted aperture* in the image center), he now has access to information contained in a wider part of the environment. From Peli et al.

subjects better performed than without in the visual search task. In the second experiment, no significant effect of the presentation of a minified edge map was found in obstacle collision risk judgment.

In [30], the author examined the impact of non-immersive head-mounted displays on the user's visual field and concluded that while the open design of such devices provides the necessary field of view required for mobility, the created relative scotoma by the device screen and the divided attention between the environment and the display may be detrimental to a safe navigation. The authors recommend to take care of the screen display positioning to control the location of the created scotoma. Training of the wearer is also recommended to use more safely and efficiently such devices.

One can note that low vision users, with reduced functional vision (e.g., reduced contrast sensitivity, impaired color vision, glare disabilities and impaired luminosity adaptation [31]), may experience further difficulties while wearing see-through HMD depending on the opacity of the device and environmental conditions. Indeed, some vision disorders like RP may additionally imply difficulties to see and to adapt to low light as well as bright light conditions. In these situations, their ability to observe simultaneously the displayed information and the environment may be severely impaired (e.g., displayed information not perceived in outdoor luminosity condition or environment visibility masked in indoor situation).

AUREVI [32] is a research project dedicated to the development of a technical aid for low vision individuals (mainly persons with RP) based on an immersive approach. The currently proposed device concept is composed of head-mounted cameras and a binocular display with screens that prevent the external light from reaching the user eyes. The later point is important, as the chosen approach is to have a complete control over the presented luminosity and visual aspect of the scene representation displayed on the screens. Controlling luminosity in real-time should for instance provide optimal display physical output regarding the user's dynamic light adaptation capability (e.g., smoothed light transition between indoor to outdoor scenes). In addition to light adaptation, other system parameters such as color and contrast are driven by the user's residual vision screening. Interestingly these parameters may be updated to account for user disease progression. Scene representation tends to be optimized for mobility tasks and optimal visual field extent and presentation, obstacle avoidance signals representation as well as dedicated image processing are currently being investigated.

4 Visual Neuro-prosthesis

Visual neuro-prostheses are an invasive technique to restore some rough form of vision in individuals suffering from late blindness due to degenerative diseases of the retina.

These devices are based on the stimulation of still functional neurons in some part of the visual pathway. By means of this stimulation, mainly electrical, it is possible to elicit visual perceptions in the implant recipient visual field. These perceptions are called phosphenes and are often described as localized blob of light approximatively circular with a Gaussian luminosity profile [33]. The generated phosphenes may have various size and apparent luminosity depending of the stimulation intensity [34]. Finally, a phosphene position in the visual field is determined by the electrode location on the retina or in the visual cortex for instance, depending of the visual neuro-prosthesis category used.

A visual neuro-prosthesis combine three main systems:

- One or more sensors providing information about the environment. Mainly, it consists of a head-worn camera as in [35] or computer-generated images [36].
- A processing unit that process and analyzes information from the sensors. Output of this system is the scene representation that will be sent to the stimulation subsystem.
- Finally, the stimulation subsystem uses the information provided by the processing stage to generate a proper stimulation at the biological level.

Phosphene generation can be achieved using various stimulation techniques: Mechanically, magnetically or electrically. Devices based on electrical stimulation are the most studied and used, we will therefore focus our presentation on these devices.

In order to better apprehend the underlying problematic of scene representation, or information transmission, through a visual neuro-prosthesis we'll give a brief overview of the main existing electrical implant categories.

4.1 Visual Neuro-prosthesis Implants

4.1.1 The Cortical Implant

This device, mainly developed by Dobelle [37], directly stimulates the primary visual cortex. It has thus the advantages to override any disorder affecting for instance the retina or the optic nerve. However, it implies a high risk surgery with possibly major postoperative complications like an epileptic seizure [38].

The relationship between localized electrical stimuli (and thus electrodes arrangement) and phosphenes location is not trivial as it is shown in Fig. 12.

4.1.2 Epiretinal Prosthesis

An epiretinal implant is an electrodes array implanted on the epiretinal side of the retina (Fig. 13). These devices are the most studied so far and several clinical trials have been performed which give information on the elicited perception characteristics and the actual performance of patients using the implant. Current Argus II

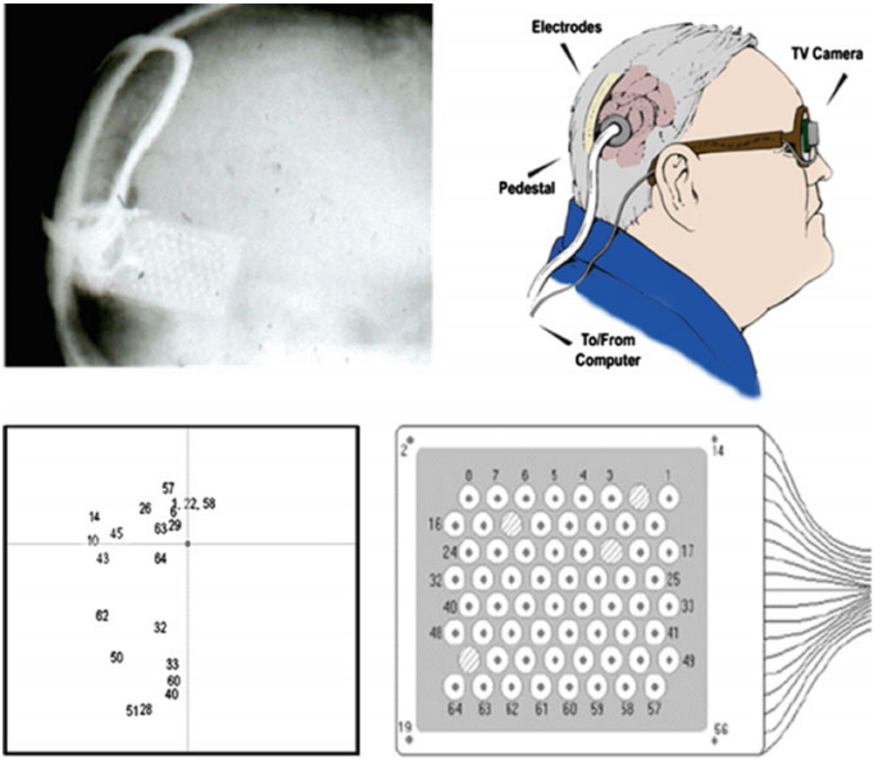


Fig. 12 *Upper Row* (*From left to Right*) X-ray image of the implant on the right occipital lobe and illustration of the information acquisition and stimulation systems of the device. *Bottom row: On the left* Map of the positions of the perceived phosphenes, *numbers* indicating which electrodes are active. *Right* schematic of the electrode array

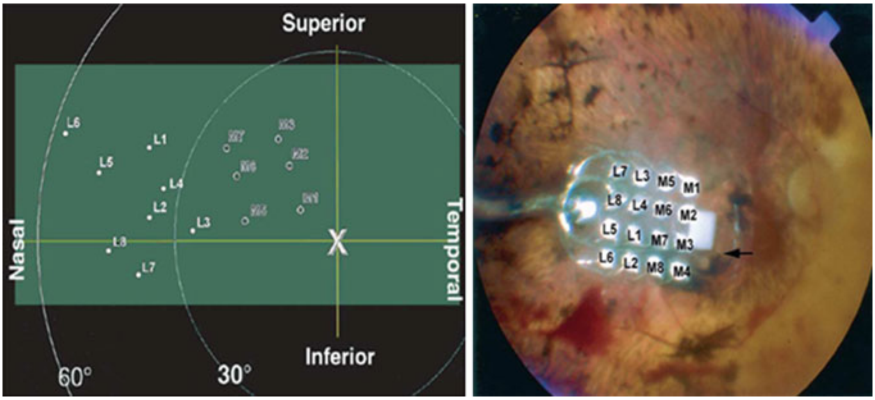


Fig. 13 Argus I epiretinal prosthesis. *Left* Perception location in the implantee visual field, *Right* Argus 1 electrode array on the retina. From Humayun et al.

(Second Sight Medical Products, Inc.) implant is composed of 60 electrodes (6 × 10 electrodes array). Interested readers may refer to [39].

4.1.3 Optic Nerve and Subretinal Implants

Two other methods exist for visual pathway stimulation: Optic nerve stimulation and subretinal implant. The former is the direct stimulation of the optic nerve through 4 fixed electrodes. Depending on the stimulation parameters, various positions and appearance (size, shape, and brightness) of phosphenes elicited in the implantee visual field can be achieved. Optic nerve stimulation devices are studied by several research groups and are notably described in [40].

For all the above presented methods, the stimulation signal is generated based on external sensors information. Therefore, in the current setup, eye movements will not allow natural exploration of the visual scene and the perceived stimuli will stay unchanged. In subretinal implants, however, the objective is to stimulate the greatest part of the remaining functional visual pathway and to use as much as possible the "natural" processing. To achieve this, nonfunctional photoreceptor of the retina are replaced by an electrodes array coupled with a photodiodes array which transform incoming external lights to electrical signal. Even if it requires amplification [41] in order to correctly stimulate the retinal cells, this technique has proven to be successfully implanted and used by patients with RP. The fading effect as evoked in [42], which corresponds to the disappearance of the visual perceptions due to a constant stimulation pattern, can be avoided using subretinal prosthesis because of the natural eye movements; whereas all other visual prosthesis using information sources external to the eye must use artificial methods to avoid such effect (e.g., adding noise to each electrode output signal). Interested readers can refer to [43].

4.2 Prosthetic Vision for Mobility

We have seen that these devices are able to generate perceptions in a form of an array of elicited phosphenes with various brightness depending on the stimulation level. Works on prosthetic vision correspond to the development of an optimal scene representation with the technical and biological constraints of a visual neuro-prosthesis.

One can note that a visual neuro-prosthesis does not allow the implantee to "see" like we commonly experience vision. Furthermore, besides the interest of exploiting the remaining functional part of the visual pathways, this device can be seen as a sensory supplementation device using the visual modality and phosphenes to transmit information. Therefore, the same problematic on how to create an optimal scene representation remains.

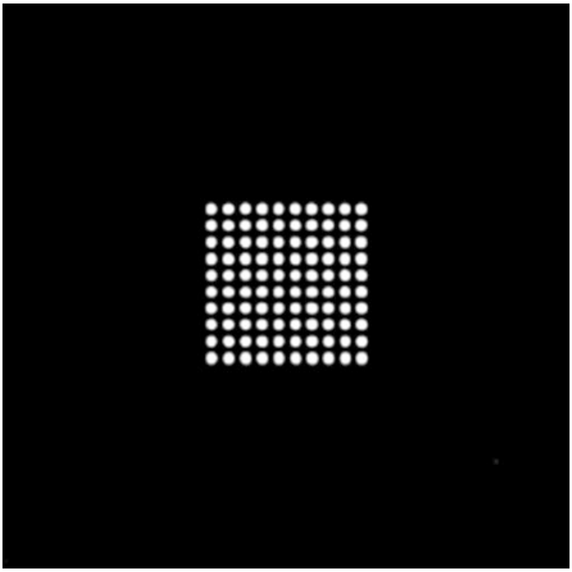


Fig. 14 Phosphenes simulation. Phosphenes are positioned following a matrix layout which only occupy a specific part of the subject visual field, the remaining visual field is represented here as the *black uniform background* (cropped here for demonstration purpose). From Cha et al.

Most of the works on prosthetic vision have been done using simulation with well-sighted subjects. This allows researchers to more easily experiment various implant characteristics number and spatial layout of the stimulation electrodes, applied image processing). These simulation studies involve displaying, on a screen or a virtual reality display, images that simulate perceptions of implanted individuals (Fig. 14).

In the literature, a majority of authors propose to use captured gray level images as input for the prosthesis. Various approaches about phosphene simulation (e.g., phosphenes simulated appearance) and, more interestingly, methods on how to transform image pixels information into scene representation suitable for the stimulation device have thus been proposed. For instance Cha et al. [35], use impulse sampling of the captured camera image through a matrix layout, which represent the position in the field of view of the phosphenes. Thus, the gray value sampled at each phosphene center position will drive the related electrical stimulation amplitude in the case of actual implant or phosphene brightness for simulation experiment.

If we consider that a phosphene represent an image region (also called receptor field) and thus few degrees of the camera field of view, some authors have proposed different techniques to estimate the corresponding phosphene value: in [44] the authors suggest to use a Gaussian filtering technique to compute the mean value of the represented pixels gray levels. Boyle et al. [45] propose to divide the image matrix into blocs of pixels. Each phosphene intensity value is then computed as the mean of the pixels gray levels of each blocs.

This averaging technique (Fig. 15), which is commonly used in prosthetic vision, can also be described as an image reduction as it simply average luminosity

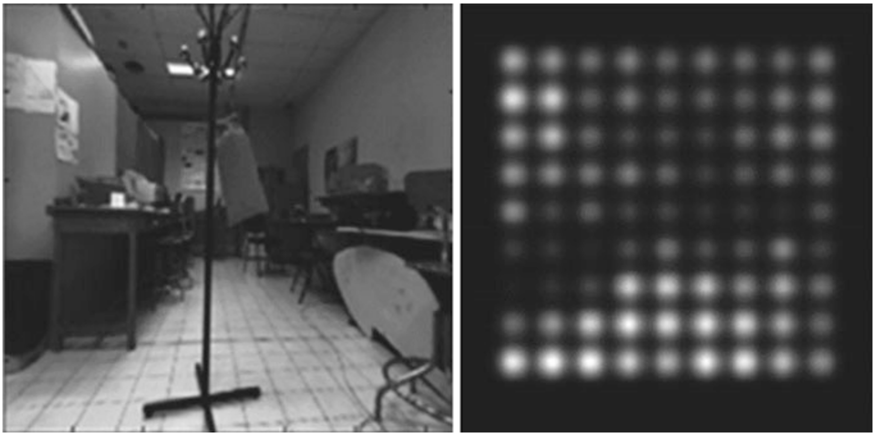


Fig. 15 Illustration of the averaging technique output with a 9 × 9 simulated electrodes array. Image are captured (*left image*) and processed using the mean calculation method to create the luminosity-based representation (*right image*) where each phosphene value corresponds to the mean gray level of the pixels in the corresponding image region. From Tatur et al.

information in each image region to obtain a lower resolution image adapted to the dimension of an implant electrodes array.

In the receptor field approach, there is a tradeoff between receptor field size and representation ambiguity. Indeed, when increasing the size of the receptor fields, more pixels regions which probably account for different objects in the scene are represented by the same phosphene which certainly makes the representation harder to decipher. Chen et al. [46] have shown that using overlapping Gaussian receptor fields seems to enhance object localization performances, at least in an artificial and highly contrasted experimental setup.

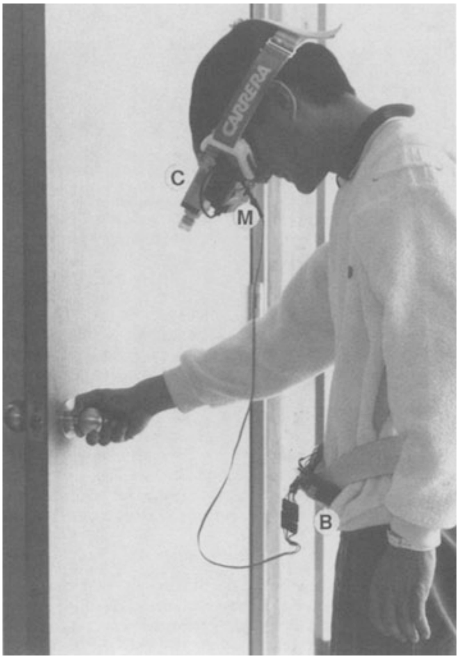
Simulation studies from Cha et al. [35] of navigation (Fig. 16) and acuity performance measures, are often presented as reference work. In their tests, they evaluated two parameters: the number of phosphenes and the presented field of view. One can note that Marron and Bailey [47] observed that visual field extent and contrast sensitivity are the two parameters that predict the most adequately performances in orientation and mobility.

They conclude that optimal performances, based on time of travel and number of contacts with the obstacles, are obtained for a field of view of 30° and a matrix of 25 × 25 regularly spaced phosphenes. The environment used for testing exhibit a highly contrasted appearance: white walls and ground, and black obstacles.

Similar results were reported by Sommerhalder et al. [48]. The author concludes that 500 stimulation points should be enough in order to perform the majority of mobility tasks. They reported that using up to 1000 stimulation points only contributes to the feeling of safety.

In [49], the authors have tested mobility performances of subjects in a real and a virtual environment. For the real environment, subjects were equipped with an

Fig. 16 Subject equipped with a simulation apparatus. A camera and a screen are mounted in a ski goggles. From Cha et al.



HMD and a head-worn camera whereas in the virtual environment, simulated phosphenes representations of computer generated-virtual view were displayed on a screen. Here again the method used for scene representation is based on the computation of the mean gray value of pixels in each image region associated to a phosphene. They concluded that as few as 60 electrodes may be enough to ensure autonomy in mobility with the requirement of intensive training. At this time, the authors were also testing the second generation of epiretinal implant, ARGUS 2.

In [50] the authors propose an interesting idea: adding electrodes, and thus phosphenes, in the periphery of the main electrodes array. In their simulation setup, height additional phosphenes are available around a 6 × 10 central array, each one representing a direction in space. The subject could ask verbally to localize various objects in the scene which will be then visually indicated by means of a blinking phosphene in the object relative direction. Additional phosphenes are here used for guidance purpose. Tatur et al. [51] proposed to use this peripheral area for obstacles proximity and motion detection in a wide field of view.

Works cited above were based on the more common general information approach. As previously discussed, in the case of visual prostheses this approach mainly propose a scene representation based on luminosity information, which imply that an electrode stimulation intensity or phosphene appearance (i.e., mainly brightness) is driven by the mean gray value of pixels in the corresponding captured image region. We will now present representative studies of the specialized approach.

In [52], the authors presented a method for scene representation dedicated to mobility. They propose to apply an image processing technique to the captured image frame which consists of the segmentation of this image in homogenous gray level regions and in the tracking of their expansion. The idea is to create an alert signal indicating the proximity or the motion of objects in some part of the camera field of view. While this idea is interesting, the lack of robustness regarding lighting condition makes this technique not operational.

In [51, 53], Tatur et al. introduced a novel approach dedicated to mobility. According to the authors, developing a method based on specialized information is a necessary step toward an efficient and functional scene representation dedicated to a specific task, like mobility in this study. The authors establish the basis of an original use of distance information as an input for scene representation in visual neuro-prostheses. They postulate that as distance-based contrasts should provide more invariant as well as less ambiguous information than mean calculation of pixel gray levels, using distance information as a substitute for luminosity information should provide an efficient representation for scene geometrical layout understanding and a safe perambulation.

Through the use of a head-worn depth sensor (i.e., stereoscopic pair of cameras) to acquire distance information of the scene, they have proposed a method to generate a depth-based representation (DBR), where the brightness of each phosphene is defined by the distance to the surrounding objects, its intensity increases as distance decreases. The information obtained from this representation is independent of the texture, reflectivity of entities and of lighting conditions. Additionally this representation directly provides ego-centered distance information of observed entities.

To create this representation, they propose to convert distance information into intensity levels, which in turn can be used to generate simulated phosphenes images for simulation studies or be use as an input for the stimulation stage of an actual prosthesis. The developed transfer function can be linear or nonlinear (Fig. 17).

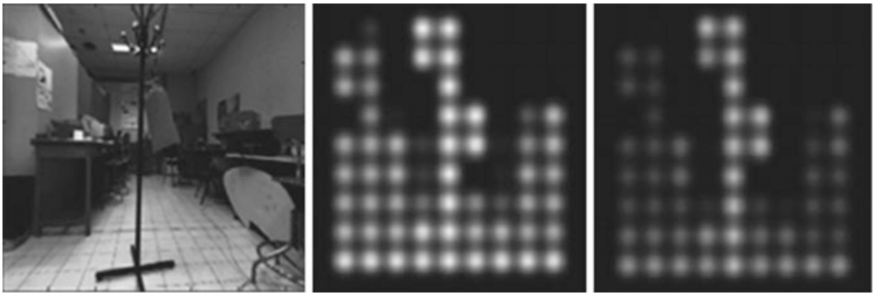


Fig. 17 Illustration of linear and non-linear transfer function. In order to represent the depth information of an observed scene (*left image*) using a depth to brightness transfer function, one can use a linear (*center image*) or non-linear methods. Non-linear method allows close distances to be represented with more intensity values and thus depth layers at close range are more contrasted. From Tatur et al.

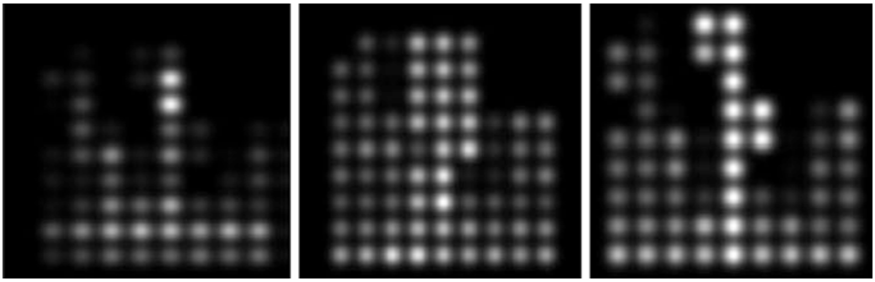


Fig. 18 Comparison of calculation methods for depth representation by phosphenes. *From left to right* Mean, minimum and median. The median method allows for more accurate object segmentation results as for instance the *black vertical object* on the foreground. From Tatur et al.

The main advantage of nonlinear conversion is that it allows enhanced contrast between closer objects by using more brightness levels to represent near distances, which seems more suitable for mobility purpose.

Similar to the mean calculation in luminosity-based representation (LBR), they provide comparison of three methods in order to obtain representative distance values at each phosphene receptor field location: arithmetic mean, the median, or the minimum of the distance values. Whereas the minimum calculation method gives an overestimate of the size of the obstacle (Fig. 18), the median value, among the other two presented methods, provide better obstacle visibility and a more accurate objects segmentation from the background and from other superimposed objects at different depth layers. Additionally, using the median calculation should mitigate the influence of local distance values that would result from depth estimation errors.

A similar approach using this depth-based representation has been tested in [54] in a real (as opposed to virtual) navigation through a simple maze with overhanging obstacles. Results indicate that the depth-based representation was more efficient than the luminosity-based one. However, the simulated electrode array dimension (30 × 30 phosphenes) was far from current epiretinal prostheses capability.

As stated by Tatur et al., a representation based on depth information may better perform than the luminosity-based representation in low-resolution prostheses since the representation directly provides the distance values and also because several processing may be applied to simplify the representation. Therefore, only relevant information can be represented. Following processing has been proposed by the authors:

- Information filtering based on distance: whether it is applied to the LBR or DBR, the objective is to remove information above a specific distance threshold and thus represented information will only be contained in a restricted volume around the user. This technique should be particularly useful in cluttered environment.

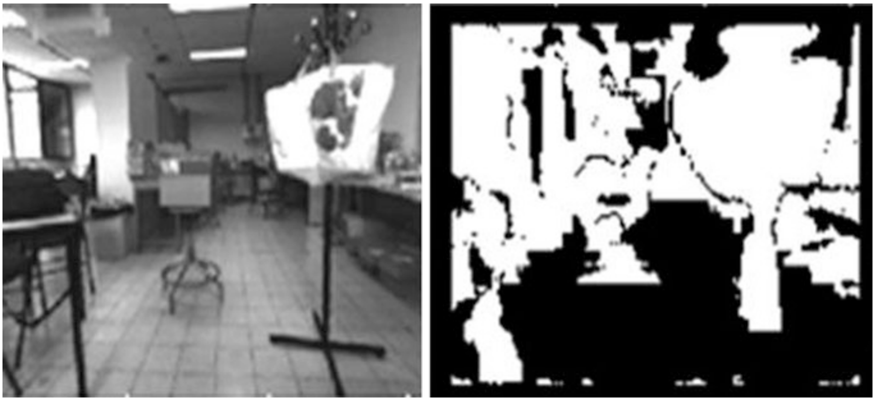


Fig. 19 Illustration of an additional information processing for simplification of the representation. *Left image* Image of a large room with obstacles. *Right image* Obstacle segmentation binary output (*white* obstacle, *black* ground or no 3D data available) using the V-Disparity algorithm. From Tatur et al.

- Ground removal or obstacles detection: using ground segmentation algorithm like V-Disparity [55, 56] it is possible to selectively present information about obstacles or obstacle-free path (Fig. 19).

Despite the advantages of depth-based representation, some difficulties remains: as only discrete intensity levels can be perceived by the implantee [57] and thus only a discrete number of different phosphene brightness values can be generated, such representation will have to cope with a trade-off between the range of presented distances and the resolution at which it will be displayed (i.e., number of brightness levels representing a range of distance values). Furthermore, despite this representation seems efficient for a safe perambulation, a navigation task requires also to be able to orient oneself. For this purpose the luminosity information can be used to acquire visual cues such as light sources (e.g., windows, ceiling lights…) as well as contrasted areas (e.g., marked pedestrian crossing). The authors propose a method to create a composite representation that combines both types of information in a unique representation based on temporal scanning of the depth layers (Fig. 20).

In this representation, the initially displayed phosphenes pattern correspond to the luminosity-based representation. Then, depending of their distance to the user, a successive highlight of the objects occurs until a previously defined maximum scanning distance have been reached. Implementation details and considerations are presented in [53]. This representation has additional advantages (see Fig. 21):

- This temporal scanning method should provide a better depth layer discrimination,
- Clues on environment geometrical layout may be inferred by the user,

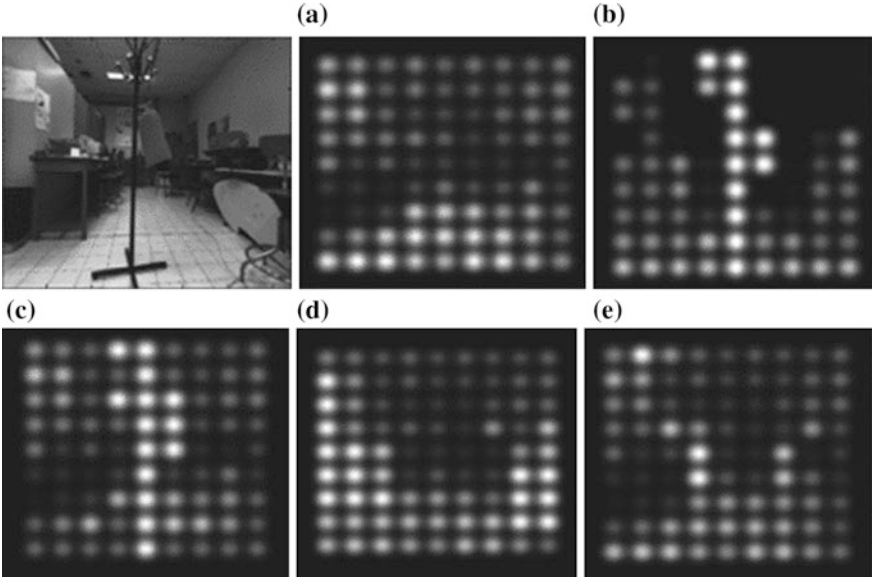


Fig. 20 Illustration of the composite representation as proposed by Tatur et al. While observing a scene using the LBR (**a**), the proposed method allows to activate a temporal scanning technique which progressively highlight objects contained in the successive depth layers of the scene (from near distances (**b**) at a time t_0 to a maximum distance (**e**) at $t_1 > t_0$). From Tatur et al.

- Progressive highlights of the depth layer should lower the ambiguity of the luminosity-based representation by giving local depth information on contrasted areas which could be misinterpreted otherwise (e.g., a dark wall could be understood as a passage).

5 Conclusion

We have seen through this chapter that various technical solutions have been proposed and recent advances seem very promising. Unfortunately most proposed solutions are for research purpose only and have not reached the market for now and may never be commercially available. This can be explained by the exploratory nature and the required multidisciplinary approach of these researches, in order to be efficiently used and accepted by visually impaired individuals. As an example of recent multidisciplinary methods, we have seen interesting approaches that take into account user's residual and functional vision as in the case of augmented reality devices which may be a first step toward a functional and adapted technical aid for low vision individuals.

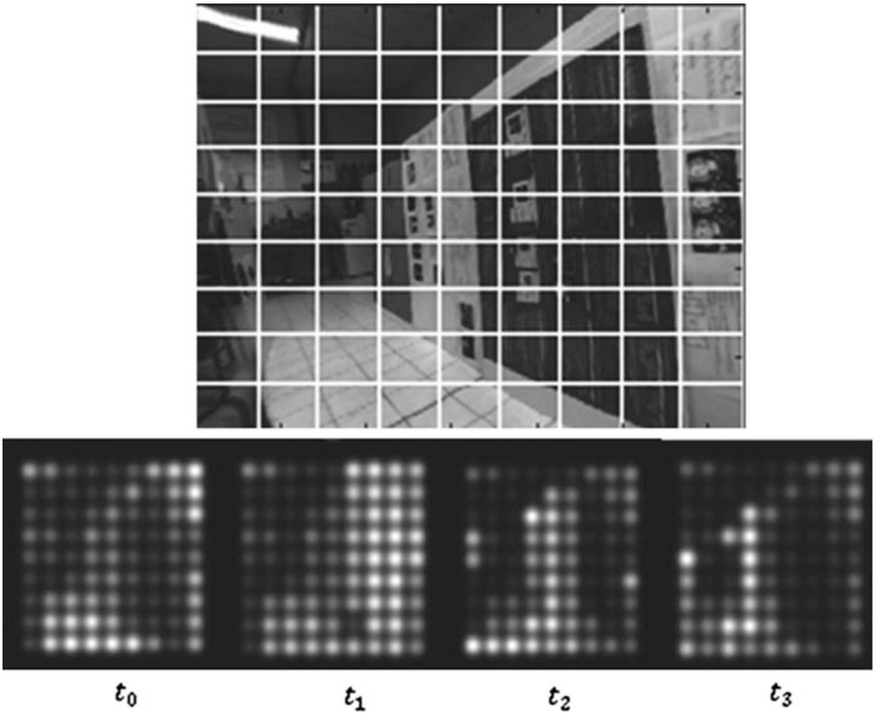


Fig. 21 Representation of a corridor-like scene. *Top row* Full resolution image (*white lines* represent phosphenes receptor field areas) of a large room with panels that create a corridor. *Bottom row* Composite representation for the time t_0 to t_3. Depth information indicates the presence of lateral obstacles that border what seems to be a corridor. A *dark region on the right side* of the image could have been interpreted as a passage with only the LBR. However, it appears to be part of the wall and could then be correctly interpreted. Vanishing point may also be detected by observing the convergence of the successive depth layers highlight

Whether it applies to mobility or any other tasks, researches still need to be conducted to define optimal scene representations adapted to the chosen category of technical aid, stimulation method, and processing strategy.

As it has been discussed through this chapter, there is still a debate whether the information should be processed or not regarding the performed task for instance, or simply "converted" in an attempt to imitate the natural visual sense input (e.g., luminosity to stimuli intensity) even if the recent literature tends to support the former approach.

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Model of Cognitive Mobility for Visually Impaired and its Experimental Validation

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1 Introduction

Human mobility is one of the most important cognitive tasks. Indeed, independent and secure mobility in a real physical space has direct impact on the quality of life, on well-being, and on integration in the numeric society. When one of our senses is faulty (e.g., visual impairment, human laterality, balance disorders, etc.) the perception of space, which usually precedes the execution of a physical movement, becomes extremely complex; the artificial simulacra of human mobility implemented in humanoid robots attest to the difficulty of understanding the cognitive function of mobility.

Indeed, the concept of a space emerges from fusion of multimodal perceptions and identification of characteristics of space relevant for mobility. However, these cognitive processes are far from being identified and well understood.

Furthermore, there is limited literature on the relationship and on the interplay between the cognitive processes which underlay human mobility, the structure (organization) of the physical space, and the design of mobility assistances.

This chapter aims to contribute to the emergence of the theoretical framework for the design of mobility aids for visually impaired people (VIP). This framework is based on the understanding and interaction (through a touch-stimulating device) with space through our senses and a new model of mobility, a holistic model.

The rest of the chapter is organized as follows. Section 2 briefly discusses different theories for emergence of space understanding from our senses, while the Sect. 3 recalls the main models of human mobility. Section 4 proposes our holistic

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new model of human cognitive mobility. The latter is based on the concept of tactile gist which reinforces the emergence of sensorimotor loops from our perceptions, the base for understanding the organization of the physical space. Section 5 addresses the validation of the tactile gist concept through several experiments. This validation relies on a purposely designed "perception-movement" experimental platform, and uses the purposely designed touch stimulation device (named TactiPad), a potential new aid for mobility assistance of visually impaired. Finally, the Sect. 6 concludes the presented research.

2 Theories for Emergence of Space Understanding

The theory of emergence of space understanding from our senses stimulations is still an open question.

Here only some main steps in the space consciousness useful for design of new mobility aids are considered; for a universal approach to the space concept, please refer to the Chap. "Living in Space. A Phenomenological Account" *of this book.*

For Kant [1], the structure of physical space emerges from the human capability to perceive the same feeling after a series of movements, and to confirm the same feeling from the same position. This series of movements establishes the relation between an external object and a feeling, i.e., the external object becomes an invariant of physical space (e.g., an obstacle for mobility).

Müller [2] defines a neurophysiological approach to perception and suggests that the perception of the space may raise from sensations transmitted by specific nerve pathways that project to particular cerebral regions. However, he does not answer how the multimodal data are fused in one concept.

For Poincaré [3], the physical space structure is not an innate faculty and does not emerge from our feelings taken separately, but from laws structuring the succession of feelings induced by space invariants (i.e., laws of simultaneous perception of all obstacles in near space).

The most recent theory—theory of sensorimotor contingencies [4–11]—extends Poincaré's position. The sensorimotor theory (SMT) states that the perception is inherently active phenomenon based on an interaction between the living (e.g., higher mammals or human being) and its environment. The SMT suggests that our brain can be considered as a system which exchanges with external world via senses (sight, touch, etc.) and effectors (hands, legs, etc.). The brain analyzes the results of movements, which it orders, using perceptions which rise from these movements. This analysis provides access to the structure and properties of the physical space and, more generally, to all sensory concepts which our brains can attach. Therefore, the perception (visual, tactile, auditory, etc.) is a capability to actively modify the sensory data using movement and attention; this modification exploits the knowledge acquired on experienced sensorimotor transformations which link action and perception.

Consequently, the SMT hypothesizes that perceptual capacities are independent of sensors and processes performed on acquired data. This leads to a sensory substitution approach to perception such as “seeing with touch” [12].

This approach has been mathematically modeled [10] by a perception space of a very high dimension (each dimension of this space corresponds to one nerve fiber!) which is embedded in a variety of low dimension with topology which is homeomorphic with a physical space. Therefore, the space perception learning is learning of a variety of the perception space. To achieve this learning, the nervous system uses the offsetability of sensory changes it perceives and specifically detection of compensable motion: a sensory change induced by the environment can be compensated by movement, or vice versa, the system then recovers its initial sensation (status). Therefore, the SMT considers that the compensability of our sensory perception is a base for the space perception. It should be stressed that this type of treatment is likely to work in the central nervous system as the cerebellum was identified for its role in sensory prediction of voluntary movements.

Furthermore, several facts from the psychology of perception confirm experimentally the relevance of the SMT as the framework for the design of assistive device for mobility.

Held and Hein’s [13] “kitten carousel” experience clearly shows that the perception and ego-motion are inherently linked and their simultaneous occurrence allows to correctly interact with the environment. This result is confirmed with visuotactile substitution systems by Bach-y-Rita, TVSS (Tactile-Vision Substitution System) and TDU (Tong Device Unit) [12, 14] and with Pissaloux’s visuotactile supplementation system named “Intelligent Glasses” [15].

Initially discussed in nineteenth century, the recent research on the phenomenon of change blindness [14, 16] showed that significant changes in a scene illumination or in a scene content can be not consciously perceived by observers if they cannot automatically capture attention, i.e., they intervene in a roundabout way (e.g., during a saccade or is concealed by a distractor). Similarly, the incremental changes can also go undetected because our perception systems (visual, auditory, tactile, etc.) do not carry out a perfect and faithful reconstruction of our environment.

As conclusion, it is possible to say the sensorimotor theory demonstrates that the space structure understanding emerges from the invariants of feelings (induced by perceptions), and from the invariants of sensorimotor loops, loops induced by the subject’s activity. To perceive a scene does not mean only to represent it but to interact with.

As a corollary to the above statements, it is possible to claim that:

- the physical space is primary and universal, and its structure [the locations of its components (objects)] may be established with respect to a reference frame;
- the simultaneous perception and action (thus the interaction with space) are necessary to understand the space structure; however, it is not yet evidences if this interplay is sufficient for understanding;

- the invariants of sensorimotor loops can be learnt and exploited during the action (e.g., during a displacement);
- the assistive technologies should reinforce the natural sensorimotor loops.

It should be noticed that Kant’s theory is a framework for path integration (or dead reckoning) paradigm, a navigation strategy taught worldwide to VIP by locomotion teachers. The ‘perception-motion’ loop is a basis for building of understanding of a space structure from its partial snapshots. We name this building process as “the space integration” paradigm.

This space integration paradigm is a framework for orientation in space and for understanding of the space structure. Consequently, with an appropriate technological aid, it would be possible to augment this understanding, to reinforce the natural mobility skills and to improve the learning process, even in the case of sensory deficit (such as vision, for example).

Therefore, as far as the design of most suitable mobility aids for VIP is considered, the following questions may be asked: (1) What is the computational model, which underlies mobility skills? (2) Which objects contribute to the space organization emergence and must be and/or may be “extracted” from the environment by the VIP during their mobility (3) When should this (these) extraction(s) be done? (4) Which sensorimotor loops are relevant for such objects perception? (5) How these sensorimotor loops can be reinforced and learnt? (6) Which pertinent feedback/presentation of these objects is useful for mobility? (7) How can we support the learning and acquisition of new mobility skills? (8) What digital technologies may be used or should be designed for such computational model implementation?

The following sections try to answer to these questions or bring some elements for such answers elaboration.

3 Models of Human Mobility

An assistance of the travel process of VIP involves two synergetic elements: a model of travel (mobility) (Sect. 3.1) and a technological assistance (Sect. 3.2) which transform the cognitive model into computational model which should be integrated in assistive devices. The state of the art of these two points are briefly discussed in this section.

3.1 Models of Mobility

A model of human mobility may be defined as a set of functions which underlay the physical mobility, e.g., all cognitive functions which allow interactions with the space.

In the previous section it was stressed that proposed so far models try to represent the physical space, and use the mobility framework known as Tolman's cognitive map [17]. This framework assumes that sensory data, extracted from the environment and filtered by the mobility task, are used for implementation of the different basic cognitive functions necessary for moving [18]. Indeed, these models assume that (1) a kind of internal map—which corresponds to the external space internal representation—is built in our brain, and (2) this static map supervises the motor function.

These models are interesting as they take into account the scene content in order to build the map. However, they differ by the data extracted from the environment and by the physical size of the near or far investigated space, [19, 20]; the size of the physical space is important as the cognitive processes underlying the mobility are different in the two spaces. The near space can be surveyed with a glance of the eye or by other means for the visually impaired (probing with a cane or other device), while the far space (or locomotor space) is too large to be seen at once, and the appropriate assistance is necessary.

Lynch's travel model [21] may be suitable for the far space. It is mainly based on trajectory geometry patterns (paths) in an (mentally) "imageable" city. This abstract model is a two-level presentation of a city for mobility purposes, as it considers that a cognitive map of a city (brain imaged city) is built by processing two kinds of elements of the environment: (1) local (e.g., paths and edges), and (2) global (e.g., city transportation's nodes and landmarks). This model does not offer enough specific data for mobility of VIP in near space (e.g., the confirmation of the journey progress). Furthermore, geometric elements of the environment (space invariants, obstacles) are supposed to be visually extracted and are related to a structured space only (a city).

Appleyard's travel model [22] may also suit the far space only, but his travel model is an abstraction of actually practiced walking patterns in a real city. Consequently, this two-level model takes into account the city global geometric layout (level 1) and its walking specificities (level 2). It is difficult to generalize these data, especially theses of level 2, for any city. As the previous model, this model does not provide enough basic data for mobility of VIP in near space; furthermore, the process of extraction of cues for mobility from the structured environment is unknown.

Loomis et al.'s [23] model of mobility is a five-component model which applies to both near and far spaces. It requires: (1) information acquisition about self-motion and landmarks; (2) path integration (memorization the sequence of path's adjacent segments and their relative spatial orientation); (3) generation of a map-like space presentation; (4) trajectory to target computing, (5) execution this trajectory. Based on experience with congenitally blind people, this model has been evaluated only on short paths without positional cues. Recent experimental works with visually impaired people [24] seem show that the VIP are not always conscious about the generation of map-like representation of the space when they walk and when they implement "automatically" well-known to them the path integration strategy.

Millar's model of mobility [25] can be used in both spaces, near and far. Based on the mobility of congenitally blind people, it links two reference frames usually used during the mobility: (1) ego-centric (or body-centerd), based on the axes of anatomy of the human body, used for execution of displacement (with constantly updated views of the space and its representation), and (2) allo-centric (or exo-centric), map-like presentation of the space used for planning of the displacement. However, the process underlying the reference frame changes and the map update are unknown.

Tversky's spatial mobility framework [26] can be used for near and far spaces. In the near space, a usual three-dimensional model of the physical space is considered, while in the far space a two-dimensional (a map) model is considered. Tversky's model clearly states that a mobility path is a mean for "linking separate views" of the space, views which depend on a reference frame attached to the space and of the metric used (usually category and not digital metric). As in Lynch's model, only geometric elements of the environment (obstacles) are supposed to be visually extracted.

Brambring two-level model [27] can be used for near and far spaces. At the first level, the locomotion process is defined as two independent tasks: object perception and orientation. Object perception is subdivided in two subtasks: obstacle detection (i.e., ahead of time detection of hazardous objects so they can be avoided), and identification of landmarks (which are very different and more various than these of sighted). Orientation is also subdivided in two subtasks: spatial orientation (considered as ability to know your current position during the walking in near space) and geographic orientation (i.e., trajectory to move from one to another point in space). In this model the concept of obstacle is not well established and only geometric elements of the environment are supposed to be considered [28]. The model does not clearly make a link with a sensorimotor loop [29].

Harper and Green's [29] model, "flow of travel," defines a (aim/aimless) travel framework as a sequential process with seven ordered steps: (1) preplan journey, (2) decision on start and end points, (3) journey, (4) track keeping, (5) in-route guidance, (6) movement to the next point, and (7) next point achievement. Similar, to Brambring's model, it extends it by adding two embedded loops: (6) to (4) and (7) to (3). The model does not consider the locomotion space preview despite of the fact that it suggests its addressing when creating new travel aid.

Maingreaud's et al. model of locomotion [30] considers a space preview by providing "obstacles–obstacles-free" presentation of the time-variant near space. The perception-motor loop is implemented through spatiotemporal modification of the preview during the displacement.

Hersh's three-level models [28] is mainly related to spatial knowledge acquisition (in near and far space). It encompasses the following steps: (1) travel process (data acquisition included), (2) cognitive map building or update, and (3) map representation. It proposes a framework for how to learn routes. However, the integration of this model into a supportive travel technology is not suggested.

The above presented mobility models—sometime named also de facto models [28]—have been frequently established from spatial description of sighted or partially sighted participants with discrete data; however, the space perception of sighted persons is very different from this of VIP [31]. Furthermore, these models are based on single journey, and lack empirical validation with a larger number of participants.

Moreover, these models are of a very high cognitive level and it is unclear how the Tolman's map are updated and how they can be translated into sensorimotor environmental data exploitable by the VIP. Indeed, only the physical obstacles are considered as mobility cues; neither navigational nor orientation cues are explicitly considered. Other multimodal cues are missing; the sensorimotor loops invariants, thus dynamic and temporal variations of space presentation are not explicitly taken into account. Therefore, the underlying cognitive processes (e.g., mobility skills generation, learning and their usage during the travel) are insufficiently addressed and cannot be integrated in the design of new assistive devices.

The brief overview of the most popular mobility assistances proposed in the next subsection confirms the above analysis.

3.2 Some Assistive Devices for VIP Mobility

Several technological solutions have been proposed in order to assist the mobility of VIP [32–34]. These aids may be classified in SSUD (Sensory SUpplementation Devices) or SSD (Sensory Substitution Devices).

SSUDs aim to provide to the end user a complementary information which reinforces the user's personal locomotion capacities and skills. Another sense (s)/modality(ies) are usually put to the contribution. This allows to provide subtle, user expected, cues which ensure that the user's main attention is on the (podo-) tactile and auditory cues of the real world, and not on the locomotion cues of the device. Such cues may be exploited during a task execution.

SSDs aim to provide to the end user the information via another (substituting) sense; they offer a new language (new code) which should be learnt independently of the initial (natural) role of this sense: a specific stimulus (a code) is associated with each object supposed to be perceived with a new sense.

This chapter concentrates on SSUD with a tactile supplementation (and not auditory as natural environmental audio cues are used by VIP when they move); for a review of SSDs, a reader may refer to [32, 33, 35].

The existing assistances of VIP mobility usually support the most popular cognitive tasks identified by the models presented in the previous section. They are: detection of some obstacles (Sect. 3.2.1), data useful for orientation or navigation and for wayfinding (Sect. 3.2.2) or for space awareness (Sect. 3.2.3).

3.2.1 Aids for Obstacle Detection

The white cane is the most popular assistance used since centuries. It provides a pointwise space (virtual) touch in a certain solid angle, which subtends the mobility, with the user as its apex. A cane provides a feedback to VIPs when a static obstacle is located on the walking surface at the distance of around 1 m. Once an obstacle is detected, the VIP should mentally elaborate an appropriated avoidance procedure by the cognitive synthesis of the discrete tactile (and/or audio) feedbacks (which includes the estimation of distance to the obstacle, its VIP-centered direction, its partial and approximate shape, etc.). The initial concept of white stick has been transformed in tools more appropriate for secure and independent mobility, especially in well structured environment such as our cities, via two generations of electronic canes.

The electronic canes of the first generation (1970–2010), transformed the white stick into a detector and localizer of obstacles in longer distances (C-5 Laser Cane, smart cane [36]), or into a detector and localizer of more complex architectural structures such as stairs going down (robotized smart cane [37]), overhanging obstacles for chest protection (C-5 Laser Cane, intelligent canes [38, 39] or into an assistant for obstacles avoidance and for change of walking directions [37] (Fig. 1). The smart cane of the University of Rouen, of the TRL 3, offers also the drift correction for a VIP [24].

These improvements usually require additional technologies such as active sensors (e.g., ultrasonic or infrared) for environmental data acquisition, and vibrotactile actuators for data feedback to the user. The frequencies and intensities of vibrations provide the information on the distance to the obstacle (a code to be learnt).

However, the distance estimated with such sensors and the imprecision of the provided information lead to a limited solid angle of space which can be investigated (frequently no more than 1 m ahead of the user). Consequently, the technological limits do not allow these canes to detect cognitive cues used by the VIP (e.g., cues for confirmation of the correct progress of the journey such as a wall to his right, or a recess in the wall). These sensors do not enable the detection of some

Fig. 1 From *left* to *right* Robotised smart cane, smart cane (K-Sonar), intelligent canes (UltraCane, TomPouce)

important obstacles such as small objects (e.g., stairs of high less than 25 cm or signs). Being guided by a cane during the obstacle avoidance may lead to spatial disorientation with more adverse consequence if the system suddenly breaks down [40]. Furthermore, being guided implies to concentrate on the locomotor capabilities of the device and not on the environmental cues which can help to understand the space and to orient in the space.

Only two intelligent canes (UltraCane, TomPouce) are currently commercialized, however, their success is limited as they only very partially use the principle of sensorimotor loop during the locomotion and the precise location of remote overhanging obstacles is very difficult.

Some of these canes are very complex to use and require concentrated attention for their operation which limits that availability for the locomotion process and environment understanding. The second generation of cane tries to overcome these limits.

3.2.2 Orientation (Navigation and Wayfinding) Aids

Orientation, a cognitive task, has not clear definition. Brabyn [41] proposed its definition as knowledge where one is in absolute terms of reference.

As such global knowledge continuously changes with the travel, we propose to define orientation as a relative knowledge of one current position in the space with respect to the journey already accomplished and the target (future) position of the journey.

However, a cognitive mobility of VIPs requires more than just this precise localization information. The existing orientation aids or orientation prototypes prove it clearly.

So far designed orientation aids can be divided into two classes: (1) a locator of a specific beacon, and (2) user's locator and tracking system.

This first class of aids is mainly based on the concept of an active beacon [42], or passive [32, 41] with audio feedbacks. In the active devices, a dedicated voice message is sent to the user (about his/her current position, for example), after the beacon has been automatically activated by a hand held device. In the case of passive devices, the user sends a signal to a beacon in order to obtain the information about his/her current place. The first version of "Talking Signs" (today named as RIAS—Remote Infrared Audible Signage) developed at the Smith-Kettlewell Institute [41], provided the voice output to make accessible dedicated indoor locations in large buildings (such as room number).

The inconveniences of the "beacon" approach is due to the fact that it is necessary to install a network of beacons, to have a dedicated pointer, to be in the range (in the cone of transmission) of the beacon's sensor and to find it; moreover, the provided information may be known to others. However, improved method is frequently applied in large public space (e.g., railway stations, airports).

The other class of orientation aids includes mainly GPS based systems (e.g., Drishti, Trekker Breeze, Captain, Casblip system/European FP6 project, Haptimap system/European FP7 project, Sound-of-Vision/H2020 FP project). They are usually stand-alone system or a specific unit of an electronic cane of second generation (2011–) (e.g., the SEES cane [43], Visio cane [44]) and they integrate a Wayfinder software (e.g., Sendero's Seeing Eye software). The latter is frequently also the person locator and tracker.

While beacon systems can be used in indoors and outdoors, the GNSS-based systems can be used only in outdoors. Both systems support the path integration strategy of navigation. However, none of the systems reinforces the user's own locomotion capacities and skills. Indeed, such systems do not provide any means to learn and to perceive the space, therefore to allow the end user to select an alternative path to reach the target or to change the path due to change of initial target. Moreover, the density of beacons may be insufficient to obtain the confirmation of the current path.

Space perception aids try to overcome these limits.

3.2.3 Space Perception (Awareness) Aids

The space perception aids aim to overcome drawbacks of detection and wayfinding devices. The tactile maps dedicated to help the VIP are tools for supporting the understanding of far space organization. At relevant scale, specific mobility maps can assist the navigation [45, 46]. The thermoformed maps are usually used for understanding city structure (Fig. 2 left), while the city concrete map (Fig. 2 right) is of very limited help for them.

Very few prototypes from academia exist (e.g., SEES cane [43]), and there is no commercially available devices [44].

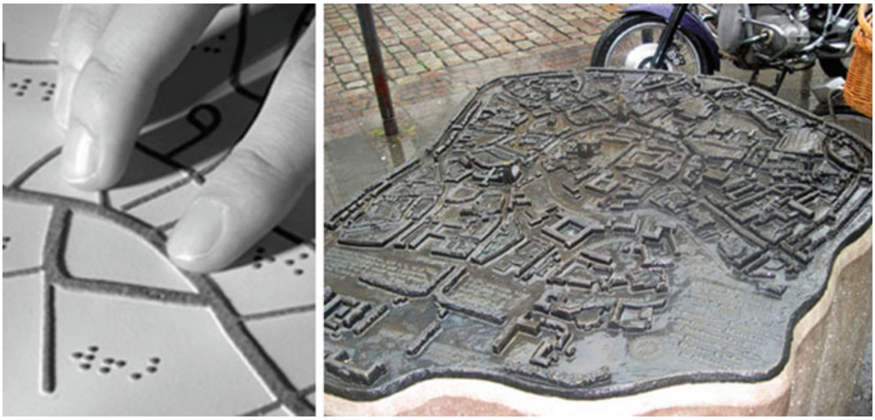


Fig. 2 Mobility map technologies: thermoformed map (Paris) and concrete map (Hamburg)

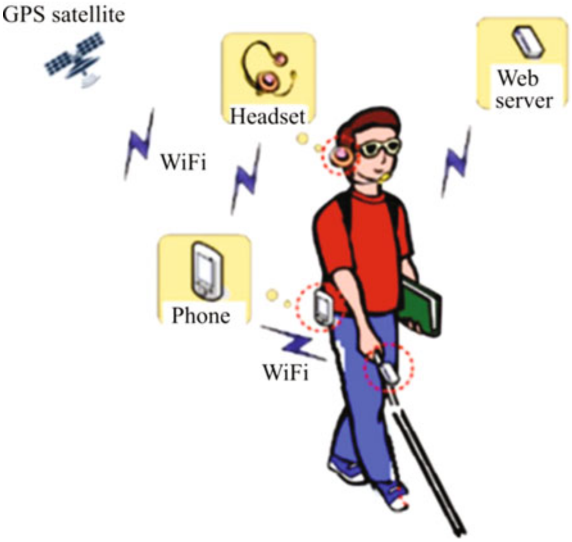


Fig. 3 SEES cane principle [43]

The SEES cane (Fig. 3) is a multimodal (tactile, voice) academic prototype (TRL 3). The SEES system provides some global services such as wayfinding assistance (via its global remote web server, iSEE), and local services such as data on the status of traffic light (via an embedded local server built in a commercial SEE phone). Data on local obstacles are provided in the same way as electronic canes of first generation do (via its smart SEE stick). The SEE phone is always connected to SEE stick through Wi-Fi.

The Netherlands regional project of I-Cane, partially financed by the European Commission, and the Visio cane project, France [44], extend the SEES cane's services by providing remote access related to data on commercial shops in a mall (opening hours, types of goods sold, etc.).

All prototypes of canes make a large usage of available digital technologies such as new sensors (e.g., camera, wheel encoder, accelerometer, and compass); the locating and tracking systems use also the Global Navigation Satellite System (GNSS).

Being based on the white cane principle which provides the pointwise information on the space, the sensorimotor loops, a base for space structure understanding and learning, are not efficiently supported. This is partly due to the fact that the target locomotion model which should support the design of mobility aids not explicitly addressed.

The next section proposes a holistic framework of locomotion and two synergetic elements which allow its integration in new mobility aids: the four-component model of mobility and the concept of tactile gist.

4 Holistic New Model of Human Cognitive Mobility

This section introduces a novel model of mobility of VIP (Sect. 4.2) and its preliminary hardware support, the TactiPad (Sect. 4.3). As the model is based on the concept of tactile gist, this section addresses this concept first (Sect. 4.1). The model aims to support natural mobility cues.

4.1 Space Presentation by a Tactile Gist

The concept of tactile gist (for mobility) finds its roots in the mobility model of ants (or rats) [47–49] and in its vision's analogue, the visual gist [50]. Indeed, "for [ants (rats)] robust scene recognition the key matter is the spatial arrangement of the objects across the scene, and not the identification of the specific individual objects" [49]; visual gist provides a rapid visual overview of a scene, i.e., an "expeditious process of seeing allowing understanding everything at once" but not in detail [50–52].

The observed 3D scene's tactile gist is a simplified presentation of its geometry (or architectural/urban) layout, orthogonally projected on a 2D surface and generated in three procedures: (1) targeted task selection (mobility in our case), (2) a 2D convex hull of 3D objects of the scene, and (3) ego-perception of the convex hull.

From computation point of view, as suggested in [53], a 3D scene tactile gist is a (simplified) 2D representation of the observed scene by a set of the nearest edges of the nearest obstacles seen by the observer, with respect to their depth in the scene, from his/her ego-centric point of view (Fig. 4). Note the notch on the 2D plan "user in the scene" which is a key point of scene presentation with a tactile gist (and originality of the proposed approach).

This presentation preserves the spatial relationships between scene's objects representation and induces a partition (or a dual representation) of the observed

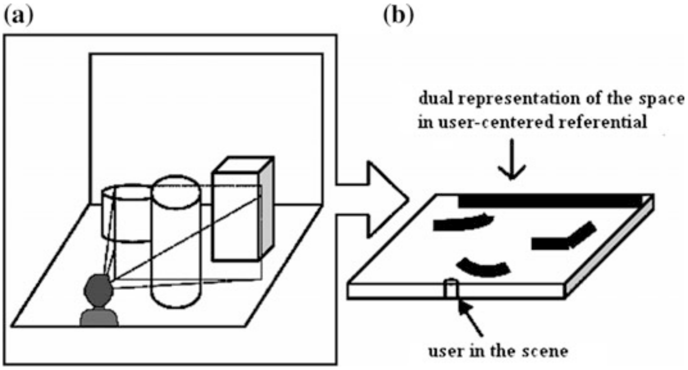


Fig. 4 From visual **a** to tactile **b** gist

scene in two zones: obstacles and obstacles-free. This partition changes with the observer's movements in the space.

The tactile gist computations are performed in the Euclidian reference frame (anchored on the subject) and using Euclidean metric.

The tactile gist scene presentation for mobility has been successfully validated with original experiments (cf. infra).

The tactile gist is a base for the computation of the refreshable tangible images which may be displayed on a touch stimulation device, such as the TactiPad, presented in the Sect. 4.3. The TactiPad was used to the experimental validation of the proposed four-component model of cognitive mobility addressed in the upcoming subsection.

4.2 Four-Element Holistic Framework of Cognitive Mobility in a Small Space

There is not yet a universal definition of the mobility, and proposed hereafter model refines and extends the model of Loomis et al. [23].

By cognitive model we understand the set of all cognitive functions which allow one to move in a space under the hypothesis that the subject is able to manage correctly his/her physical posture (motor functions).

The mobility is a complex cognitive function, and may be analyzed as a four-dimensional problem—the mobility function subclasses—such as walking, orientation, space awareness and navigation. Each of these fundamental functions is defined by its space domain and the human consciousness level attached to it [23, 34]. There is no cognitive hierarchy between these functions. These functions are interrelated, but their precise inter dependency in still open research question.

Walking can be defined as a low conscious (cognitive) aimless displacement in the near space. Walking encompasses more elementary functions such as obstacle (ego-centered) detection and localization (e.g., distance and direction estimation between subject and obstacles), (approximate) estimation of the obstacle form and its height, and (allo-centered) distance estimation of between obstacles [54, 55]. Walking can include a trace function, i.e., memorization of the set of spatially adjacent segments and their relative orientations with respect to one's (ego-centric) position, if the path integration is the used navigation strategy.

The orientation (usually designed by a limitative term "wayfinding") can be defined as a set of continuous processes which allow to know one's current position in space, to update his/her the target position, and to estimate the direction to take from one's current position in order to reach one's target, the target recognition, etc. Orientation implies the capability of planning a specific route to reach the target location from the current point [8], which implies being aware of the space structure/organization.

The space awareness (or space knowledge) is especially linked to the near space and requires the high consciousness level. It can be defined by several cognitive parameters such as (1) the forming and making use of the space representation where the travel takes place, (2) the forming and making use of urban and social data (e.g., name of the street, library, bakery, etc.), (3) acquisition and combination of spatiotemporal sensory stimuli such as landmarks, clues, cues, traffic light status, road works, smells, (podo-)tactile stimuli, temperature), (4) the acquisition of unpredictable events, (5) anticipation of events. Space awareness acquisition may include a map function, i.e., the space presentation with a (geographic or not) map. The space awareness requires a good memory (and its efficient support), and the fast and reliable matching capability between memorized and real-time perceived (tactile gist of the) scene.

Navigation, a high level cognitive task, is performed in all spaces and results from implementation of all listed above functions while traveling. From a computational point of view, the navigation is an iterative process, the “perception-orientation-space_awarness” loop which achieves once the target location is reached.

Navigation develops the anticipation skills in order to update the navigation strategy to real locomotion needs.

A successful locomotion requires cooperation of several elements, some of them performed simultaneously other sequentially. Examples of simultaneous events are: (1) path integration and space integration [33] and drift correction; (2) data on landmark and obstacles acquisition; (3) orientation and path trace building; (4) sociourban data perception and space integration.

Sensorimotor loops execution, location updates, and the drift correction are inherently sequential.

The proposed new model is a holistic framework for mobility. It includes all interactions functions between subject and space, as all these interactions are necessary to understand and act in the space. Moreover, the identified interactions.

All elementary functions of the proposed model can be efficiently implemented with existing digital technologies. The next paragraph presents the TactiPad, an academic numeric prototype which may be a new type of mobility aid.

4.3 TactiPad, a Hardware Support for a Near Space Refreshable Tangible Presentation with Tactile Gist

The TactiPad (Fig. 5) is an academic prototype of a tangible refreshable multimodal interface. In general, the TactiPad is a support for refreshable tangible images (e.g., geographic map, tactile presentation of faces, tactile presentation of images, etc.).

The interface is similar to a Braille matrix of 8 × 8 taxels (tactile elements); a 8-dot Braille cell is a TactiPad of 2 × 4 taxels (dots). However, contrary to the Braille cells, TactiPad is a Braille surface realized with shape memory alloy technology [40, 54, 56]. The whole system is a cube of 8 cm of edge length and weights 200 g; it is a wearable embedded device.

Fig. 5 TactiPad, a touch-stimulating refreshable tangible multimodal interface

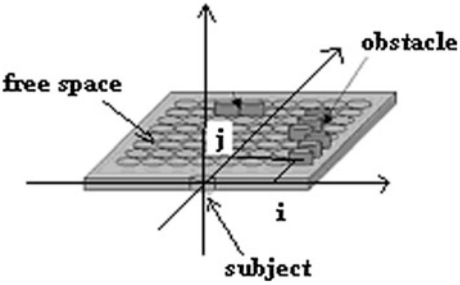


Fig. 6 TactiPad: a 2D matrix of tactile individually programmable elements with its reference frame

Taxels' interspacing is this of Braille cell, i.e., 2.6 mm; the TactiPad's display refresh rate is 1.5 Hz (which is suitable with the human cognitive ability to perceive a tactile stimulation). Each taxel is individually controlled, i.e., programmable.

The TactiPad is used for space presentation with a tactile gist display. From computational point of view, a TactiPad is a binary matrix where an obstacle (or a part of it) is coded "1" (raised taxel) and obstacles-free zones are coded "0" (taxel in a lower position) (cf. Fig. 6). The origin of the 3D reference frame attached to the represented space corresponds to the subject's position in the represented scene and is materialized with a notch on the board of the TactiPad (Fig. 6). This reference frame is necessary for metric data supply for mobility.

The TactiPad provides simultaneously ego- and allo-centric displays of a scene represented by a tactile gist. TactiPad surface can be manually explored actively or passively. The active strategies involve unconstrained hand movements and different exploration strategies can be used for its surface scanning (e.g., lateral motion, i.e., moving the fingers back and forth across a texture or feature), contour following (i.e., tracing an edge within the image) and whole-hand exploration of global shape [53]. The passive strategies use usually the whole hand superposed over the touch stimulation surface.

This first prototype of TactiPad (TRL 4) is mainly the device for obstacle detection and space representation (with tactile gist). However, it already offers the hardware support for space awareness and for orientation. A prolonged push on a raised taxel provides simple voice synthesized information selected with a (voice) menu.

The second prototype of the TactiPad, under design (with 32 × 32 taxels), includes all functions for orientation (implemented with technologies similar to these used in the SEES cane, internet/Cloud technologies included). The hardware and software of this new prototype will provide a navigational assistance through continuous background communication with available networks and clouds.

5 Experimental Validation of Tactile Gist as a Support for Sensorimotor Loops

The experiments validating the tactile gist as a support for sensorimotor loops learning and recalling, have been implemented on dedicated "Perception-Movement Platform" (PMP) (Sect. 5.1) which allow the participants (Sect. 5.2) to perform a set of cognitive tasks such as association of cognitive information with perceived tactile stimuli or basic mobility tasks (Sect. 5.3) using TactiPad.

5.1 Perception-Movement Platform

The built "Perception-Movement Platform" (PMP) is presented on Fig. 7.

The PMP is a dedicated 5 m × 7 m room, containing a set of static, but moveable, obstacles. The platform global image is acquired with a camera overhanging (6 m) the platform [56]. The navigating subject wears a bicolor hat; colors order indicates the subject's face (gaze) orientation. This hat is tracked by the vision system overlooking the platform. The vision system transforms the platform's image in front of the subject (ego- or first person image) into the relevant tactile gist presentation of the scene and displays it on the TactiPad carried by the subject.

5.2 Participants

The presented experiments involved twenty blindfolded healthy volunteers, who had never used a tactile surface before and five congenitally blind subjects. Seventeen subjects were men and eight women, aged from 19 to 59 years. Three participants were left-handed.

An initial questionnaire assessed participants preferred hand, their ability to use touch-stimulating interfaces (touch screens) and to play video games.

During the navigation on the platform, the environmental audio cues were rendered inaudible by broadcasting a pink noise in the participants' earphones. All subjects participated in all tasks.

5.3 Proposed Experiments for Validation of the Tactile Gist as a Support for Sensorimotor Loop

Two classes of experiments have been implemented: perception of tactile stimuli (Sect. 5.3.1) and elementary mobility tasks (Sect. 5.3.2). Only one participant was performing a task at any one time.

5.3.1 Perception of Tactile Stimuli

The working hypothesis assumes that the perception of tactile stimulus is successful if the participant is able to associate a cognitive information with it, such as a recognized object or identified moving direction.

Experimental Conditions

These experiments duration was about 30 min. Participants were seated in front of the TactiPad (Fig. 8). In order to recognize the displayed tactile data, subjects explored the tactile surface with a hand. This manual exploration was not constrained; the used hand, the number of hands, the exploration strategy and the perception time were selected by the participant.

Subjects' answers have been recorded by the experimenter. At the end of the experiment, the assistance provided in the tactile stimuli recognition and overall feelings of participants about the device were recorded.

Two types of stimuli have been evaluated: static (Sect. Tactile Perception of Static Shapes) and dynamic (Sect. Recognition of Patterns' Motion Direction).

Fig. 7 PMP, "perception-movement" platform

Tactile Perception of Static Shapes

The main goal of this task (T1) was to identify which geometric parameters of tactile shapes are relevant for tactile presentation of scene.

The working hypotheses of this task are the following:

- H1.1 a line segment is easiest to recognize;
- H1.2 the size of the patterns impacts the quality and speed of recognition; the biggest tactile patterns are easier to recognize that the pattern is of medium or small size;
- H1.3 surface patterns are more difficult to recognize than the framed patterns.

Protocol

A sequence of 8 static shapes (Fig. 9) were displayed on the TactiPad. A displayed sequence was supposed to produce a lot of changes in fingertips' tactile stimulation (i.e., generate as much as possible the tactile gradients of amplitudes as big as possible) [57].

The three following parameters (independent variables) of a displayed pattern have been considered: shape (square, triangle, circle, or line segment), size (small 4 × 4 taxels, medium 6 × 6 taxels, and large 8 × 8 taxels), and type (surface (or full) or framed).

Results

Table 1 summarizes the collected results; they correspond to the average value for the whole tested population. The average was used because of very inhomogeneous characteristics of participants.

The collected results show that:

- line segment is the easiest pattern to recognize; independently of its size, the recognition rate is around 87%;
- the average recognition rate of a triangle is 62.3%;

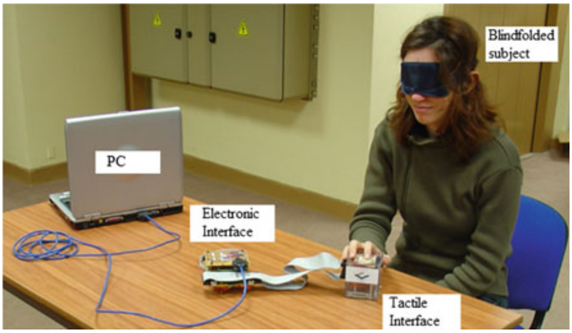


Fig. 8 Experimental setup for tactile stimuli cognitive perception

Table 1 Geometric figure recognition

Geometric figure	Type	Recognition rate (%)	Mean time of recognition (s)	Most frequently confused with
Big size shapes (8 × 8 taxels)				
Square	Surface	34	21	A triangle, a line, a circle
Square	Framed	40	19	A circle
Circle	Surface	5	7	A square
Circle	Framed	89	32	A square
Triangle	Surface	57	23	A square, a circle
Triangle	Framed	79	52	A square
Line segment		93	21	A square
Medium size shapes (6 × 6 taxels)				
Square	Surface	40	25	A circle
Square	Framed	63	42	A triangle, a line
Circle	Surface	25	24	A triangle
Circle	Framed	20	41	A triangle
Triangle	Surface	75	10	A circle, a square, a line
Triangle	Framed	63	31	A circle
Line segment		90	27	A triangle
Small size shapes (4 × 4 taxels)				
Square	Surface	50	42	A triangle, a circle
Square	Framed	60	43	A triangle,
Circle	Surface	20	33	A triangle, a circle
Circle	Framed	20	47	A triangle, a square
Triangle	Surface	25	16	A circle, a line
Triangle	Framed	75	20	A line
Line segment		77	27	A triangle, a circle, a square

- squares and circles (full/surface patterns) are the most difficult to recognize; their respective recognition rate, independently of size and type, is 47.8 and 28.8%.

Therefore, the H1.1 is confirmed by the obtained results.

As far as the geometric figure size is considered (regardless figure shape and type), it can be observed that the average recognition rate of big patterns is 56.7% (with the average recognition time of 25 s), this for medium pattern is 53.7% (with the average recognition time of 28.6 s) and this for small patterns is 46.7% (and the average recognition time is 32.6 s). The big line segment was recognized faster than medium and small size segment (21 s vs. 27 s and 27 s). For other geometric figures, their type (full/surface or framed) has the impact on the recognition time.

Therefore, the H1.2 is confirmed by the obtained results.

As far as the geometric figure type is considered (full/surface or framed), the line segment is excludes from the analysis as its type is surface and framed at the same time.

The average recognition rate of big surface patterns is 32% (within 17 s), while big framed patterns is 69% (within 34 s).The average recognition rate of medium surface patterns is 47% (within 20 s), while medium framed patterns is 48% (within 29 s).The average recognition rate of small surface patterns is 32% (within 30 s), while small framed patterns is 52% (within 37 s). Therefore, the recognition rate of framed shapes is better (and faster) than this of surface shapes.

The analysis of the impact of geometric figure form and its tactile type presentation leads to the following results: the recognition rate of the surface square is 43% versus 53% for framed shapes (regardless of size); these for circle are, respectively, 17 and 43%; and these for triangle are 52 and 72%. Regardless of geometric figure form and its size, the framed shapes are better recognized than their surface counterparts.

Therefore, the H1.3 is confirmed by the obtained results.

Almost all subjects have selected the active exploration of the tactile surface through lateral whole-hand exploration of global shape (movements over the global shape), complemented sometime by contour following (i.e., tracing an edge within the image). The stimulation of the touch with a fixed raised taxels was appreciated as it was possible to make several explorations of the same pattern with movements of any direction.

Results interpretation

The tactile pattern recognition rate is based on the tactile stimulation of the mechanoreceptors of fingertips. Strongest mechanical stimulation (lower the physiologically acceptable) induces biggest tactile gradient and better and faster perception of the stimuli. However, in the related experiments, all taxels have been raised on the same height in order to form cognitively coherent 2D geometric figures.

The recognition speed is not really pertinent, as it is shown in subsequent experiments, the learning process plays an important role in recognition time and it is put in motion since the beginning of experiments.

The main results are related to the type of figure presentation: the framed type seems to be more appropriate than its surface counterpart.

The better recognition of framed shapes can be explained by the more frequent stimulation of fingertip mechanoreceptors compared to the surface shapes. Indeed, the most frequently observed strategy for TactiPad surface exploration was lateral whole-hand exploration of global shape, complemented sometime by contour following. This means that the finger spatial parallelism plays a role in recognition; this point was always commented by the participants. Moreover, the changes of mechanoreceptor stimulation (tactile gradient) occur more frequently on framed presentations than in surface presentations. These results are similar to the results by Hein and Held, the theory of human receptors [13].

Contours following were mainly used for confirmation of the shape discovered with the whole hand with its mental image of the geometric figure (memorized visually).

Therefore, it is possible to claim that the recognition of static framed tactile patterns with a fixed display is possible under the condition of the pattern appropriate size and type (framed).

The TactiPad fixed (and not vibrating) display of patterns allows the end user to better perceive them and does not generate any physiological and psychological discomfort. The good appropriation of the fixed tactile display may be expected.

The TactiPad resolution (8 * 8 taxels, 2.6 mm intertaxel distance) could explain a confusion in perception of different patterns. This means that the better (and faster?) cognitive integration of sparse tactile information may be obtained with a smaller intertaxel distance (i.e., with a touch stimulation device of higher resolution). The weak recognition rate of the small patterns (such as a line segment of 4 taxels) could confirm this hypothesis.

The tactile shapes' recognition may support the obstacles' recognition in the mobility tasks.

Recognition of Patterns' Motion Direction

Goal

The purpose of this task (T2) was to determine if the tactile moving pattern can allow the recognition of motion direction.

Tested hypotheses

We wanted to check if a tactile arrow, being a tactile representation of a visual pointer of direction, could play the same role as its visual equivalent, i.e., be an indicator of the moving pattern direction.

The working hypotheses of this task are the following:

H 2.1 The moving framed shapes (framed arrow, line segment) allows better recognition of the direction motion.
H2.2 The framed medium size arrow is the best support for the motion direction recognition.
H2.3 Directions North and South are easier to recognize than East and West.

Protocol

Simple patterns moving in a predefined direction have been displayed on the TactiPad. The pattern motion has been implemented by shifting the display of the same pattern on adjacent taxels at different, temporally adjacent, time slots (every 300 ms); therefore a shape needs 2.4 s in order to sweep the entire tactile surface.

The two consecutive directions were randomly selected but in such a way that they offered the maximal stimulation of fingertips.

The three independent parameters of experiment were: the shape, the shape size and the motion direction. The possible values of shape were: surface arrow (triangle), framed arrow, and line segment (cf. Fig. 10); the possible sizes were big (8 taxels) or medium (6 taxels) for triangle/arrow base; the size of line segment was 8 taxels; the possible motion directions were orthogonal (North, East, West and South or NEWS).

Participants should recognize the motion direction (one from expected NEWS directions) but not the displayed form. If the wrong answer is obtained the same shape is displayed second time (but no more).

The TactiPad surface exploration methods were free.

Collected results

Table 2 summarizes the results of NEWS directions recognition for two moving shapes (line segment and arrows) with three representations of an arrow (surface, big framed and medium framed). These results are averaged by the size of the tested population. The average was used because of very inhomogeneous characteristics of participants.

The average recognition rate of the movement direction with framed patterns is 85% and significantly better than with surface patterns (57%). The best recognition rate of the moving direction is with the framed arrow (medium arrow: 88%). Therefore, moving framed shapes are generally better recognized that surface shapes what confirms the H2.1.

The average recognition time of a direction is 20 s (with 16 s for north and 17 s for south direction).

The moving direction recognition rate with a line segment is 73%, this with a framed arrow is 82% and this with a surface arrow (triangle) is 57% only.

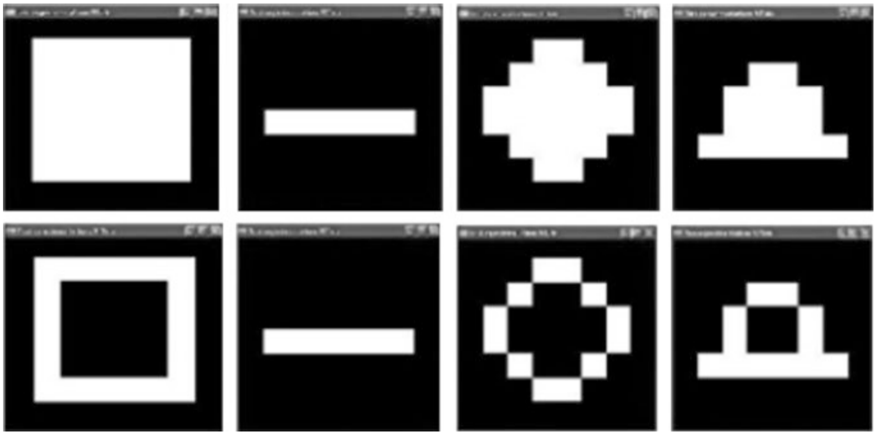


Fig. 9 Evaluated tactile patterns (*white*/*black* pixels: active/inactive taxels)

Table 2 Collected results for motion direction recognition

Moving shape	Type	Size	Recognition rate	Mean time of recognition
NORTH direction				
Arrow	Framed	Big	88	13
Arrow	Framed	Medium	100	15
Arrow	Surface	Medium	28	17
Line segment		Big	83	20
EAST direction				
Arrow	Framed	Big	79	16
Arrow	Framed	Medium	85	38
Arrow	Surface	Medium	80	14
Line segment		Big	89	16
WEST direction				
Arrow	Framed	Big	81	13
Arrow	Framed	Medium	76	47
Arrow	Surface	Medium	58	28
Line segment		Big	91	16
SOUTH direction				
Arrow	Framed	Big	78	11
Arrow	Framed	Medium	90	26
Arrow	Surface	Medium	60	15
Line segment		Big	27	15

Therefore, the framed medium size arrow is the best support for the motion direction recognition. Therefore, the hypothesis H2.2 is validated.

The average rate of direction recognition is of 75%. The north and south directions recognition with a medium framed triangle was better and faster than the recognition of east and west directions. The north directions recognition with a line segment is of 83%, while the south direction recognition is only 27%.

Therefore, the hypothesis H2.3 is validated.

Moreover, the direction recognition with a surface arrow is close to 57%. These results confirm those of triangle recognition.

All subjects have selected a passive exploration of the tactile surface, i.e., they put their fingertips on the TactiPad and tried to understand the motion direction.

The participants have pointed out the confusion in recognition: the big triangle has been frequently mixed with a line segment moving in a diagonal direction.

The movement recognition is better for framed patterns than for full ones.

Results interpretation

A shape moving to the North (N) or to the South (S) direction follows the fingers' "natural" direction; this could be an explanation of the best recognition of these directions. This result suggests also that the loss of physical continuity between adjacent fingers during TactiPad passive exploration, when information moves in a direction perpendicular to "fingers' directions," increases the cognitive load for east and west directions recognition.

The tactile arrow pattern is relevant for healthy subjects who know the meaning of a visual arrow for their spatial orientation.

On the average, the recognition of directions seems a less complex cognitive task that the pattern recognition because of the quantity of data which should be analyzed.

The direction recognition (and the recognition time) are important for exploitation of data provided by dynamic maps represented by the tactile gist.

Remarks on Tactile Pattern Recognition

For the two experiments presented above, standard deviation shows a very large intersubject variability. This variability allows to establish the very preliminary rules for tactile pattern perception and recognition. This variability explains why the average values of collected results have been presented here. Therefore, evaluations, with large number of participants, are necessary.

The average success rates of tactile pattern recognition tasks with the TactiPad are very promising. Consequently it seems that the tactile gist will allow to track the evolution of object frontiers during the mobility. Finally, the collected results show that the TactiPad it is possible support for the "tactile gist."

5.3.2 Elementary Mobility Tasks

The considered mobility tasks (T3–T6) are the following: obstacles awareness (Sect. Obstacle Awareness, T3), homing (Sect. Homing and Obstacle Avoidance, T4), passage localization and passage size estimation (Sect. Passage Localization and Passage Size Estimation, T5) and large space understanding from local views (Sect. Large Space Understanding: Space Integration, T6).These tasks have been selected as they are baselines for other more complex mobility tasks.

These tasks provide a support for sensorimotor loops as the participants explore the space with a TactiPad and perform movement according the their understanding of space presented on the TactiPad by a tactile gist and by the tactile feedback provided by the TactiPad once they performed the movement.

All tasks have been implemented on dedicated "Perception-Movement Platform" (PMP) were six rectangular obstacles were randomly placed; five of them were near the platform edges and the sixth was located randomly inside the platform (cf. Fig. 7).

Obstacle Awareness

Goal

This task T3 overall goal was to check whether or not the tactile gist can provide efficient assistance for independent mobility by providing data on obstacles in the space near by the participant.

Tested hypothesis

Tested hypothesis was the following:

H3: Tactile interface can provide the necessary and sufficient information to assist obstacle avoidance (obstacle awareness).

Protocol

The task has three stages: oral explanation, learning, and execution (navigation).

During the explanation, a participant learnt about the relationships between tactile displays provided by the TactiPad and obstacles localized on the PMP platform. The notch on the TactiPad surface represents participant in the space and the obstacles localized on the platform in front of the him/her are represented by a tactile patterns. The TactiPad notch allows to estimate the ego-centered distance to obstacles. The tactile patterns and their place on the TactiPad change with participants movements.

During the second stage the participant, with the assistance, learnt how to use the TactiPad when moving and how to match the real obstacles with their representations and positions on the TactiPad.

During the navigation, once the participant has the bicolor cap and the blinding mask, (s)he was positioned at a random location on the platform and walked freely in it using the TactiPad and trying to avoid the obstacles localized on the platform (Fig. 11). This was the only instruction given to the participant.

During the navigation, the PMP registered participants trajectories, the corresponding direction of the gaze (approximated with the bicolor hat) and the time and location of each obstacle contact.

At the end of the experiment still blindfolded participant was accompanied to a room for final discussion and filling a semi-structured questionnaire.

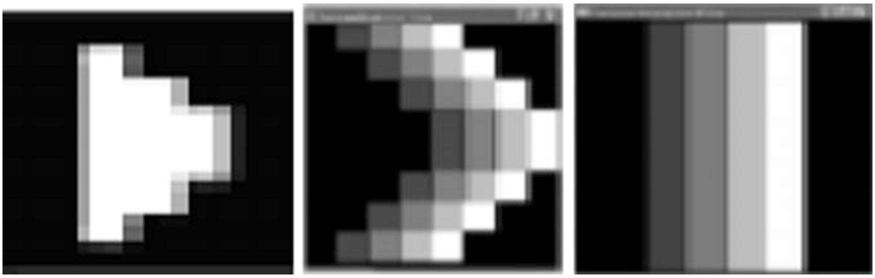


Fig. 10 *Arrows* (surface and framed) and *line segment* "moving" in the East direction

Collected results

Values of three parameters were registered:

- the number of physical contacts (bumps) during the considered slot time;
- the effectively explored physical space;
- the space perceived.

The average number (for all participants) of contacts with obstacles during 10 min free walking on the PMP platform was 5. Figure 12 summarizes the results on frequency of visiting different places of the PMP platform during the free walking stage; the left image shows the orthogonal view of the PMP platform (navigation space) while the right image shows the frequency of participant presence in this place of the platform (the average value for all participants). It should be observed that all participants visited 24 same places on the platform (Fig. 12 right, white pixels); the most frequently observed gaze orientation, shown with a white arrow, confirms that participants perceived well the obstacles with the TactiPad.

The effectively explored physical space is defined as the surface physically explored by subject during the walking in the considered slot time; it is quantified by as a surface of all rectangles attached to subject's trajectory (a rectangle being defined by the subject shoulders' width and subject's one-step forward distance).

Figure 13a image shows an example of a participant's explored space (participant's trajectory, and Fig. 13b) image perceived space (in the sense of the above definition) associated to the explored space. The collected results show that over a time slot of 10 min, on the average 72% of the available area was explored.

The space perceived via TactiPad is the surface of physical space displayed on the TactiPad during the walking in the considered slot time (Fig. 13b). The

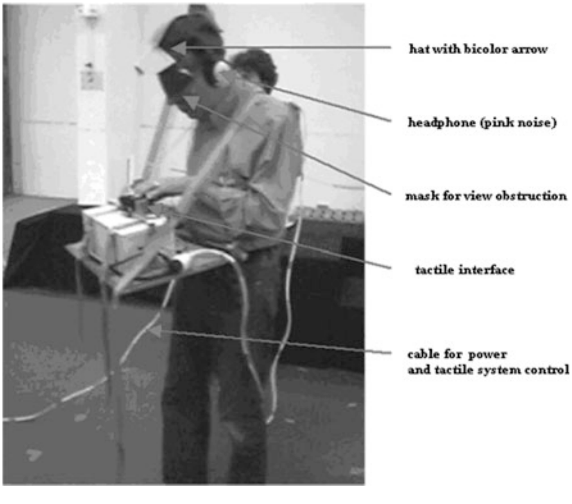


Fig. 11 Participant wearing bi color hat, headset (for the pink noise) and carrying the TactiPad (at the height of his belt)

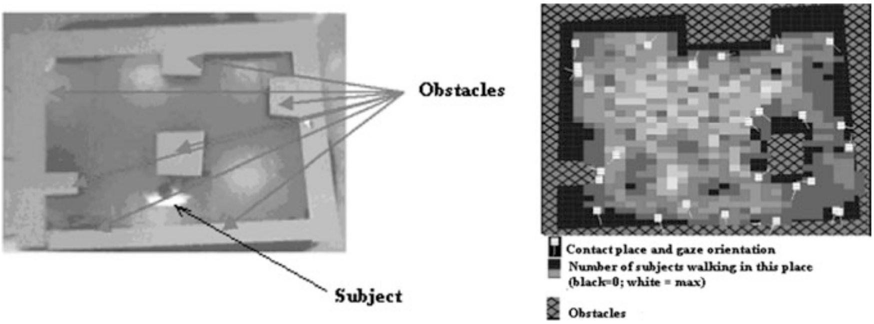


Fig. 12 PMP navigational space (*right*) and frequency of different places of the PMP platform

collected results show that over a time slot of 10 min, on the average 96% of available area was perceived.

Results interpretation

From the obtained results (Fig. 12b) it is possible to conclude that subjects had a good awareness of obstacles' presence as the number of contacts is low (5) with respect to the large part of the explored space (96%).

The few contacts are often due to misjudgment of distance. Indeed, often it was noted that the participant was aware of the presence of obstacle (he turns around, he very gently approached it), but finally he overestimated the distance to it. He did one step too to the obstacle and touched it with his foot.

This result is consistent with results concerning pattern recognition on the interface: poor spatial stimuli resolution is certainly the cause. Indeed, participants "feel" an obstacle to reach them when they are approaching, but they have a poor definition of its spatial position and, therefore, the relationship between their own speed and approach speed of obstacle on the interface.

As far as the timing of these contacts is considered, it is not possible to establish a rule. For the contacts which occur at the beginning of free navigation we can assume that the lack of participant familiarity with the interface and tactile navigation causes their occurrence; for those of the end of the experiment, which were less frequent that at the beginning, we can assume they are due to participant fatigue. However, the increased familiarity with the interface and the lower number of bumps in the end of experiments confirm that TactiPad provides an assistance for sensorimotor loops (tactile perception and mobility).

The obtained results indicate that the TactiPad allowed participants to determine the presence of obstacles and their approximate locations. Therefore, the hypothesis H3 is validated.

Homing and Obstacle Avoidance

Goal

Task T4, "*Homing*", is a "sensorimotor" version of the classic triangle (homing vector) task [23]). Knowing that there is an obstacle on the PMP platform, the subject was asked to turn around it and return to his/her starting point.

T4 investigates possibility the pertinence of the TactiPad, a refreshable tangible to localize an object, to correctly estimate the distance between subject and obstacle, to approximate shape necessary to walk around and to assist the orientation in space (assist the return to the starting point).

Tested hypotheses were the following:

H4.1 A tactile device allows to localize an obstacle.
H4.2 The tactile gist allows to estimate the shape of an obstacle in order to walk around it.
H4.3 The sole tactile gist does not assist the return to the starting point.

Experimental protocol

Each participant was explained that "(s)he will be placed at the entrance point of a PMP platform which is limited by a continuous wall; one obstacle is randomly placed on the platform. (S)He is asked to find this obstacle, take a walk around it and return to the platform entrance."

(S)He was also told that one taxel of the TactiPad matches à real surface of about 30 cm × 30 cm. There was no indication on the shape of the obstacle.

The expected outcomes were: (1) subject's itinerary which was filmed by the camera overhanging the platform, and (2) the sentence "I have finished".

Once the subject gave authorization to proceed, (s)he put the bi color hat on his/her head and put the TactiPad on (Fig. 11), then was conducted to platform entrance.

Collected results

Figure 14 shows five examples of the filmed trajectories. It can be observed that all participants have correctly localized the obstacle and none of them have touched it. In the whole tested population of 20 participants, 19 subjects did at least one entire tour around the obstacle without touching it; so task success rate is 95%. Therefore, the hypothesis H4.1 is validated (this result confirms these obtained in T3).

Figure 14 shows that four over five subjects made the least one entire tour around the obstacle. In the whole tested population of 20 participants, 17 subjects did at least one entire tour around the obstacle, i.e., task success rate is 85%. Therefore, the hypothesis H4.2 is validated, i.e., the tactile gist allows to roughly estimate the shape of an obstacle (and avoid it).

As far as 'the return to the starting point" is considered, it can be concluded from Fig. 14 that only two subjects (B and C) returned to their starting point; some subjects are convinced to return to their starting point while in reality they did ¾ or 1.5 or of the

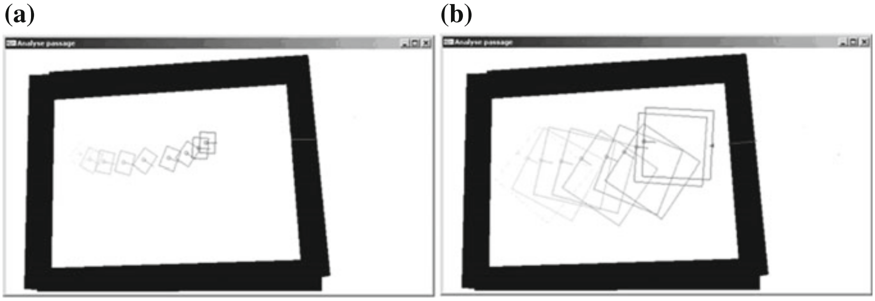


Fig. 13 **a** Effectively explored space, **b** effectively perceived space

cycles. In the whole tested population of 20 participants, 7 subjects returned to their starting point; most frequently, participants did between ¾ and 2.5 of the cycles. Therefore, the task success rate is 35% and the hypothesis H4.3 is validated: the sole tactile gist does not assist efficiently the return to the starting point.

Different subjects used different strategies for walking around the obstacle. From Fig. 14, it can be observed that the subject C (a congenitally blind subject) took the obstacle as it rotation center; others (e.g., the subject A, late blind) walked around the obstacle touching it virtually (through the TactiPad), from time to time, in order to know whether or not the obstacle is behind him.

Interpretation of the results

The mistakes made by users are particularly interesting as they seem confident of being returned to their starting point. Also, even if they do not appear to totally trust to the gist presentation, they use it and rely on it to locate in the global environment.

It should be observed that the users use information which changes with their displacement; moreover, they foresee it as “inaccurate”. Therefore, their behavior observed through mobility trajectory can be explained in two ways:

- participants lacked of confidence in the vestibular information or did not pay attention to their ego-motion, therefore they absolutely seek to use another—exogenous—information,
- the participants seek to merge the (variable) gist information with their own vestibular information (with different success).

Concerning the validity of tactile gist for the homing task, it is necessary to find others distinctive features (visual or not) in the environment which would stabilize the purely geometric data of regularly (especially symmetrically) shaped obstacles. They can be iconic (poster, color, other object, etc.) or based on the geometry of the whole scene itself [58].

In this task, despite of the necessary orientation data, only the geometrical indications (cues) have been extractable due to the proposed tactile gist presentation of a scene. This point of the design of the TactiPad should be improved; operations such as zoom-in/out or TactiPad better resolution which will allow to obtain fine distinctive details of the obstacle shape should be considered.

From semi-structured questionnaires, participants pretend the more successful use of strategies in which the focus is on the "homing." They used the interface to avoid the obstacle without using the displayed geometry as a salient index of the environment, which could serve as a reference when performing the task.

This experiment showed that tactile gist and a refreshable tangible device seem pertinent for obstacle localization while walking. However, the usage of purely geometrical local representation of an obstacle may be insufficient in some navigation tasks. Other distinctive features and/or the geometry of the whole environment should be considered. Finally, it seems that the TactiPad reinforces the natural mobility skills of the participants as the obstacle was never touched by any of the 20 participants.

The post-experimental discussions highlighted the fact that subjects who performed better in this task implemented a strategy where returning to the starting point was their main goal. They used the TactiPad only for obstacle avoidance and not for using the platform's geometry as a salient feature of the environment. This confirms that the classic mobility strategies learnt in our youth are local, and that the possibility to have access to a representation of the larger space is not used by these strategies. This opportunity for building new mobility strategies and for better spatial understanding should be evaluated in depth.

Finally, participants appreciated the continuous support of the TactiPad as they walked around the platform. This shows that the TactiPad provides a good support for memorization (and recall) of the sensorimotor loops.

The impact of gender and congenital blindness for the execution of this task was not investigated due to the small number (20) of participants.

Passage Localization and Passage Size Estimation

Goal

The goal of the T5, "*Size of passage estimation*" (affordance) which constitutes a baseline for the T6, is localization of a passage (e.g., a doorway, at the center, to the right, to the left) and estimation of its size from TactiPad display before deciding to pass through or not. Moreover, it investigates the pertinence of the TactiPad for the rough estimation of a metric distance.

Therefore, this task investigated how well the untrained participants can locate a passage and estimate its size.

Tested hypotheses were the following:

H5.1 it is possible to locate/recognize the passage
H5.2 it is possible estimate the size of passage from its tactile presentation and to learn metric distance using a touch stimulation unit.

Protocol

He was seated on a chair in front of a table placed in the middle of the PMP platform. The TactiPad was put on the table in front of the user. Each participant wore an eye mask (if necessary).

This task has two independent parameters (cf. Fig. 15):

- passage location with respect to the subject position (no passage, located centrally, to the left, to the right);
- sizes of the passage small (2-taxel), medium (3-taxel) and large (4-taxel).

A passage location were randomly displayed on the TactiPad; the size of the displayed passage was also randomly selected (by a dedicated software).

The participant was told that “(s)he will be placed in a virtual space where a wall may have a passage. His/her task is to determine whether or not there is a passage in this wall and, if the passage is present, (s)he should estimate if its size allows him/her to pass through.”

The participant was also told that one TactiPad’s taxel matches à real surface of about 30 cm × 30 cm, and that the average width between the human’ shoulders is around 60 cm. Expected answers were: “no passage,” “no” if he cannot pass, and “left” , “right” or “central”.

Once the subject gave the authorization to proceed, a wall was displayed on the TactiPad. Once (s)he gave an answer, a new wall was displayed.

The task was repeated twice in order to evaluate the learning effect (the first five attempts were considered as learning).

Collected results

Table 3 shows the evolution of the passage location recognition rate as a function of its location in the wall. Learning increases, in a homogeneous way, the correct recognition rate by roughly 50%.

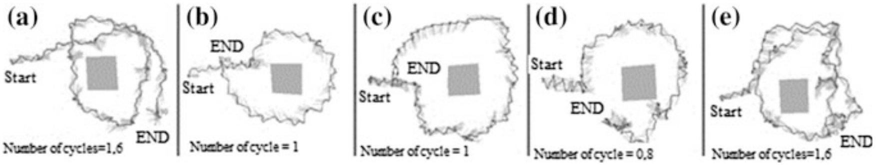


Fig. 14 Trajectories of five subjects during the homing task

Table 3 Statistics for passage localization

Passage localization	Centrally located (%)	Left located (%)	Right located (%)
Correct recognition without learning	52	42	63
Correct recognition with learning	93	65	95

Table 4 Statistics for passage size estimation

Percentage (%) of the recognized passage	Small (%)	Medium (%)	Large (%)
Correct recognition without learning	25	64	69
Correct recognition with learning	66	89	95

Table 5 Recognition time of a passage

The recognition time	Average (in s)	Minimal (in s)	Maximal (in s)
Average time without learning	18.9	6.8	41.5
Average time with learning	12.2	7.5	20.9

Therefore, the hypothesis H5.1 is confirmed.

Table 4 shows the evolution of the recognition rate as a function of the passage size. As previously, learning increases the recognition rate, especially for the small passage (by 100%).

Table 5 shows the evolution of the response time with and without the learning. Globally, the average response time of participants is low.

The results summarized in Table 5 confirm the hypothesis H5.2.

Results interpretation

This task has twofold meaning: affordance (possibility to perceive) and object recognition (passage location). The results obtained clearly show that learning significantly improves the success rate of passage size estimation.

Several factors can influence such results: the ability of the participant to project him(her)self in the tactile gist representation of the passage provided by the TactiPad, the experience (learning of the representation), or the repetition of the stimulations generated by the TactiPad (which probably increases the subject's sensitivity).

The recognition rate of the left passage is far less than other, which may be explained by the subjects laterality; indeed, as all subjects used their right hand for TactiPad exploration, the left part of the tactile display was considered as the central part.

Tactile gist seems to be an efficient way for stationary representation of the scene, and the Tactipad is an efficient support and allows fast and easy execution of the task and learning; moreover, it seems that the TactiPad reinforces the natural perception skills of the participants.

This task shows clearly that it is possible to learn the metric relationships between distances displayed on the TactiPad and physical space (once the scaling factor—here 1 taxel = 30 cm × 30 cm—is known).

The effects of gender and congenital blindness on this task execution were again not investigated due to the small number (25) of participants. However, the subject's laterality may influence this task recognition rate.

Large Space Understanding: Space Integration

The task T6, "Apartment geometry (layout) reconstruction from walking" is a cognitively complex task as the participant should collate isolated tactile representations of each room in the global architecture of the apartment.

Therefore, this task investigated how well the untrained participants are able to recognize the architectural layout of the whole apartment from isolated tactile layouts of its rooms investigated sequentially during the virtual navigation in this apartment.

This task investigates also if the tactile gist and TactiPad contribute to the emergence of an efficient representation of a more global space (the apartment) from its local representations (individual rooms). This task is named space integration.

Tested hypothesis is the following:

H6 it is possible to reconstructing the geometry of a larger space from tactile local snapshots of different subparts of this space.

Protocol

Each participant was seated on a chair in front of a table placed in the middle of the PMP platform. The TactiPad was put on the table in front of the user.

(S)he was told "you will virtually navigate in a 4-room apartment, from room 1 to room 4, using the TactiPad." The TactiPad will provide you a layout of a room seen from its entry door (there is one entrance to the room and one exit). You can explore its tactile presentation as long as you wish. Once you declare that you fully understand the current display, you will be asked to report its layout as a drawing.

If you want to move to the next room you simply say: "next room please," and the next room will be displayed on the TactiPad and you repeat the process until you finish room 4 (end); there is no obstacle on your itinerary when you navigate from one room to the next.

At the end, your four drawings will be concatenated in order to get the total explored space."

Figure 16a gives the layout of the investigated 4-room apartment, while Fig. 16b shows the 4 snapshots of each room and their tactile coding on the TactiPad. The exploration time of each drawing has been registered.

Collected results

This task is composed of two interrelated subtasks: the recognition of layouts of each room from its tactile (gist) presentation, and (mental) integration of the whole apartment layout from rooms' layouts. Figure 17 shows an example of drawings made by 4 blindfolded subjects (from top to bottom) in the first sub-task. These drawings are similar to the space representation displayed on the tactile device

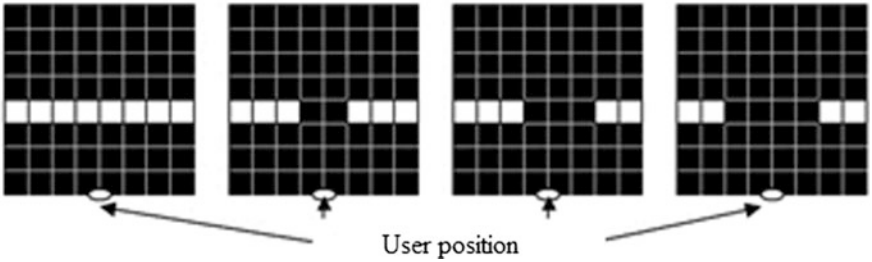


Fig. 15 Passage size estimation task: four investigated cases

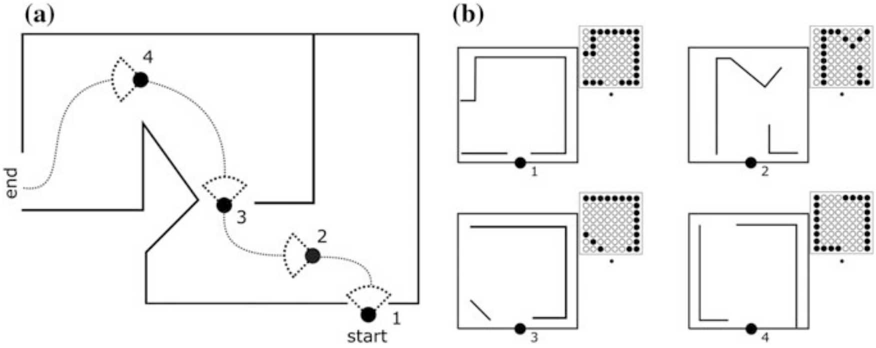


Fig. 16 **a** 4 room apartment and the virtual navigation path (from 1 to 4); a cone in each point 1–4 approximates participant's field of view; **b** tactile snapshots of each room displayed on the TactiPad from the entrance point to each room (1–4). The *black point* on the tactile display border represents the participant's position in the observed scene

(Fig. 16b), especially those done by subject 4. Data collected from all 20 sighted participants show that roughly 70% of them (14 participants) have correctly recognized the layout of each room.

During the implementation of the second subtask, each participant was asked to select the layout between four supposed to match the layout of the explored apartment. During the selection, sighted subjects used their own drawings, while the congenitally blind subjects used the tactile (fixed) drawing made by volunteer undergraduate students using their textual descriptions of each room layout. Figure 18 shows the proposed layouts, where B is the correct layout .

In response to question after the experiments, almost all the participants stated that they proceeded by elimination of the less probable layouts. For example, in room (1), subject 1 had translated both entrance parallel-to-him/her lines into perpendicular lines. He did not detect the triangle in room (2) but had acceptably represented rooms (3) and (4). When reconstructing the whole layout, based on his first drawing, subject 1 first has discarded layouts A and B. From his second

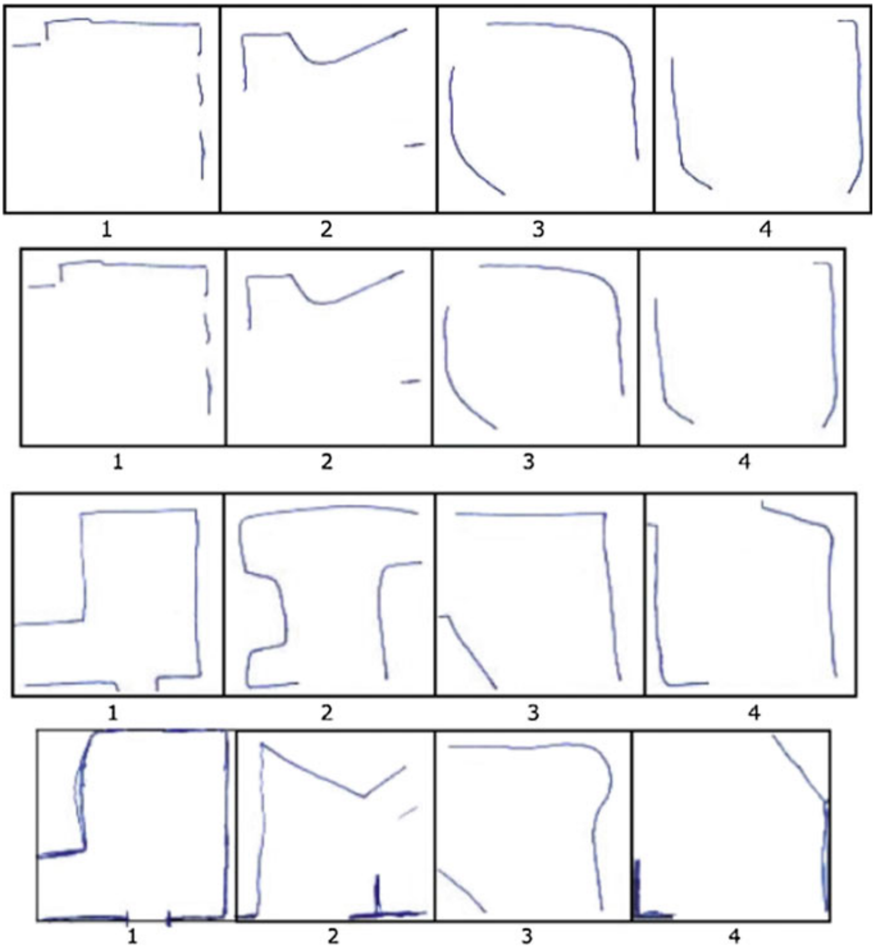


Fig. 17 Drawings of four blindfolded subjects 1–4 from *top to bottom* (lower line) of their understanding of the tactily explored rooms (1–4)

drawing, he pointed to the layout D but his third drawing suggested him that he missed the triangle in the second drawing, so he pointed then to C. The door's position in the fourth drawing had indicated that there is an error in C and subject-1 reconsidered his B choice. From C and B, subject-1 was more persuaded by the first drawing and finally he chose the layout C.

From the obtained results it is possible to claim that the hypothesis H6 is confirmed.

Figure 19 shows the space exploration and recognition time per subject. The recognition time for five subjects, except number 2, has decreased with the exploration time, and the average recognition time is around 3 min for totally inexperienced subjects.

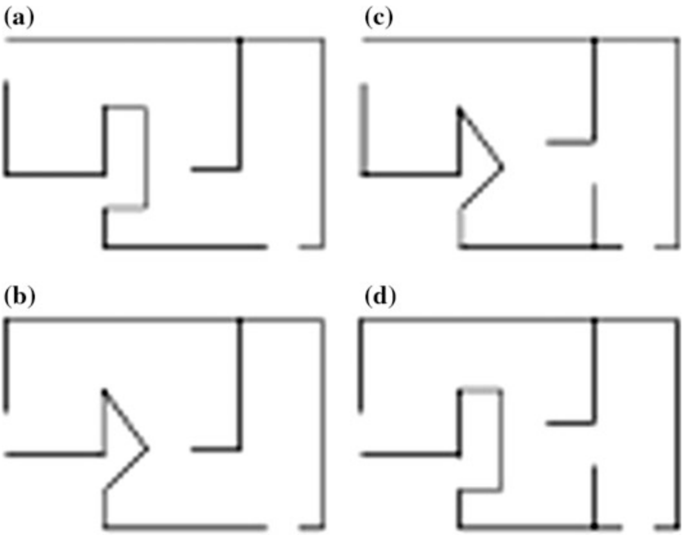
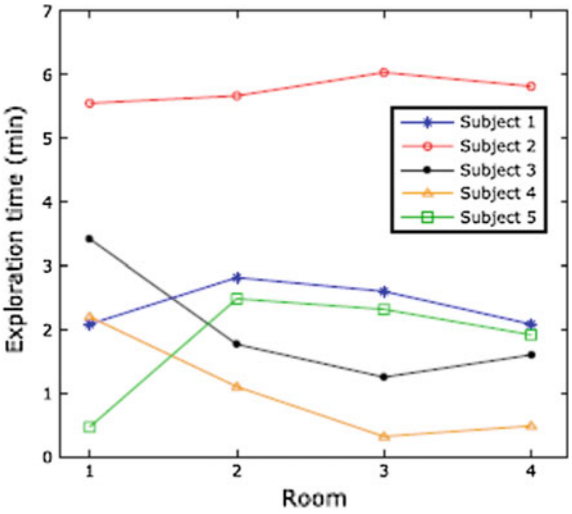


Fig. 18 Four proposed layouts of the apartment for space (whole apartment layout) integration

Fig. 19 Exploration times per subject in the apartment layout recognition task from tactile gist and participant's drawings



It was observed that the fastest subjects tried to obtain a global idea of the space explored (by rapid scanning of the whole tactile surface), while the slower subjects have tempted to get the details of the scene elements (and have used the sequential follow during the representation acquisition).

Results interpretation

An analysis of drawing of each room confirms that the tactile gist is suitable for geometric layouts presentation and that the spatial information displayed on a touch stimulation device, such as the TactiPad, may be is pertinent to support of the tactile gist, and to support the emergence of the high level concepts.

The obtained results show that the apartment overview was more effective and accurate for all participants.

A methodological lesson has been learnt: the first attempt to reconstruct the apartment did not involve any drawings; however it was realized that this space integration task was too complex as the subjects were capable of remembering only the tactile layout of the last explored room and just for a short period of time (in the average 20 s). Consequently, this experiment methodology was modified to the presented above.

The post-experiment discussions with participants confirm the pertinence of the TactiPad as a tactile gist display unit. The decrease of the room's exploration time shows that the learning of tactile gist presentations is fast. This suggests a learning/habituation to the task, a pertinence of the tactile gist concept for layout presentations, and a potential fast appropriation of the TactiPad as a mobility aid.

The importance of gender and the effects of blindness on task execution were not investigated.

5.4 Summary of Main Results

The obtained results can be summarized as follows: it is possible using tactile gist displayed on a touch stimulation surface such as TactiPad

1. To recognize basic geometric figures, especially these represented by frames (T1).
2. To determine the direction of motion of a (medium) arrow with the best recognition of North and South movement (T2).
3. To detect and avoid obstacles after a very short learning period (T3).
4. To detect a passage and to estimate its size (T5).
5. To establish metric relationship between data displayed on the TactiPad and in real scene (T5).
6. To integrated large space from its subparts' snapshots tactily displayed (T6).
7. To navigate while avoiding obstacles and represent and create obstacle layouts, using egocentric and allocentric representation of the space (T6).

The sole tactile gist representation of a scene local geometry is insufficient to orient in the space, and especially to return to the starting point (T4). A holistic approach is necessary.

All these results confirm the pertinence of the TactiPad as a refreshable tangible device for tactile gist display and space representation, and confirm the importance of sensorimotor loops in the space integration paradigm (through the reconstruction of the apartment's whole layout).

It should be stressed that the age and education level impacted the tactile gist understanding. All six senior participants, with very heterogeneous level of education, needed more time to understand the code; young subjects, all graduates with bachelor level at minimum, tried to use the device without understanding its working principle and finally, after few minutes of the usage of the TactiPad, they declared they understood the basis of its use. However, these two different learning strategies—one based on a deep understanding of the tool and the other based on a 'trial and error' approach, did not influence the success rate in task execution. These results confirm similar findings already obtained [56].

Finally, the proposed experiments can be considered as first benchmark for evaluation and comparison of mobility assistive devices.

6 Conclusion

This chapter summarizes the results related to the mobility of the visually impaired (VI) and the design of assistive technology. It stresses that the mobility is a complex high-level cognitive task and requires the holistic approach.

The limitations of existing models of mobility are overcome with the aid of the proposed new holistic four-component model of mobility, which includes (1) obstacle detection, (2) space orientation (3) awareness, and (4) motor displacement.

The significant characteristics of this model are that (1) the mobility process is considered as a sensorimotor loop which contributes to continuous updates of the cognitive map, for interaction with the space when moving and for understanding the space, (2) tactile gist, an appropriate tactile space representation (or coding) for mobility, which is easy to understand and exploit when moving.

Implemented experiments validate the proposed model with voluntary, congenitally blind and blindfolded, subjects. They investigated some basic (elementary) cognitive functions which subtend the mobility such as perception of tactile geometric figure (static and dynamic), obstacle detection and egocentric localization, passage and space metric data estimation, homing tasks and space integration.

The experiments were implemented on a purpose built "perception-motor" platform (PMP), and used the TactiPad, a digital tangible unit for tactile gist display.

The collected results confirm the pertinence of the proposed mobility framework as a support for natural mobility skills and sensorimotor loops.

The proposed model also constitutes a framework for the design of new mobility aids. Indeed, the TactiPad is a refreshable tangible unit, and its preliminary formative evaluation through the proposed experiments shows that it supplements or improves a person's natural ability to navigate.

The TactiPad may support different mobility strategies used by VI such perimeter, gridline, reference point and cyclic searches [33], which may be useful for the implementation of other cognitive tasks. Therefore, the TactiPad allows not only seamless navigation (as a non-focal activity), but also other interactive tasks in 2D and 3D spaces.

Future research should continue in several directions. It is mandatory to identify all the elementary functions of mobility and evaluate them experimentally; all stakeholders (including locomotion teachers) must be involved.

The extensive evaluation of all the above-mentioned tasks should include a large number of subjects with various degrees of visual impairment (and ARMD subjects included) in order to obtain statistically valid results. This summative evaluation must be done in virtual and real physical environments.

The simple rules for automatic generation of tactile gist presentation of the near mobility space are necessary.

The bigger size and higher resolution of the TactiPad (with zoom in/out displays) is necessary for a better mediation between space and VI. The pure geometric representation of the space with a tactile gist should be complete with other modalities for orientation purposes.

A new assistive device based on the TactiPad should offer several services involving new digital technologies such as access to the Internet, to the Cloud, to Wi-Fi, to the current status of the environment (e.g., status of the traffic lights, knowledge of road works).

All these improvements should allow the elaboration of new mobility strategies.

Finally, the importance of gender, blindness, age, and education levels should be investigated with a larger cohort of participants. This will allow us to adapt the TactiPad capability to subjects having different cognitive profiles and transform the TactiPad into a more efficient tool for access to space by visually impaired.

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Solid: A Model to Analyse the Accessibility of Transport Systems for Visually Impaired People

Gérard Uzan and Peter Wagstaff

1 Introduction

In order to maintain a fulfilling and active lifestyle it is essential to remain mobile and have access to public buildings, transport and sources of information as well as to have a full social and professional life and interact with other members of society. This is particularly true for the disabled and elderly and over the last few years there is increasing interest in responding to their needs and introducing practical solutions to guarantee mobility and accessibility. More than 80 million people in the EU have some kind of disability and this figure is expected to increase to around 120 million by 2020, due to the effects of the ageing population, so the challenges faced to ensure full accessibility for all are enormous.

Beyond the economic and political considerations, one of the primary elements in the change of attitudes leading to progress is the increased understanding of what constitutes disability through the establishment of the international classification of disability by the WHO [1]. Applying the model of Philip Wood, the International Classification of Disability of the WHO defined the situation of disability in 1980 as an individual characteristic, independent of situations and resulting from the interaction between a disability, incapacity and handicap. In 2001 the International Classification of Functioning, Disability and Health (ICF) by the WHO [2] adopted a model based on an analysis of actions, interactions and activities of daily living defining disability no longer as the personal difficulty of an individual, but the result of the combination for one or several individuals of the context of an activity and the tasks to be performed.

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To reduce or eliminate the situation of disability it is important to act on the context and the conditions necessary to carry out the tasks. The initiative should not only be left to individuals acting alone, charitable organisations or NGO's, but should be an aim of society and concern all those involved in designing or organising the framework of our daily living and social life. The universal availability of accessible equipment or devices, accessible transport and accessible private or public premises and infrastructure are central to these objectives. This may be attained through the creation of new norms and obligations through new regulations, the development and implementation of solutions for the accessibility of public places and essential equipment and the political will to apply the concepts of universal design. The right to accessibility is now enshrined in the United Nations Convention for the Rights of Persons with Disabilities (UNCRPD), which was ratified by the EU in 2011 and has since been enacted in most member countries.

2 Accessibility

The principle of accessibility applies to two essential spheres of daily life: digital space (documents and applications on computers, smart phones, websites, interactive terminals and various types of machines such as ATMs) and also to physical spaces (vehicles, buildings, infrastructure and spaces open to the public in the framework of personal, professional or health requirements as well as highways and public transport). Work on accessibility standards, in addition to its territorial implications (national, continental or international) is the result of compromises between organisations, companies and local and national governments, whose cultural characteristics and efficiency in the deployment of solutions reflect the position of each actor. We should note that standardisation has even more impact on policies and decision-making, since it is inscribed in national regulations protecting human rights and normally associated with strict delays for implementation and sanctions for failure. This integration of standards in law presupposes that it is feasible to implement practical solutions for all users in each application in technical and economic terms. Recently we have seen that the economic crisis in Europe has resulted in some failures in completing the goals announced in this area for 2015. We therefore distinguish normative and regulatory or contractual accessibility integrating effective accessibility on the one hand from the constraints of feasibility and the reality of access resulting from the measures taken. For architects and engineers, normative accessibility as translated into standards and regulations is not sufficient. Effective accessibility requires that more specific questions be raised to validate the feasible solutions, which should ensure:

(a) Real access for people in difficulty based on the criterion of effectiveness.
(b) Completion of tasks in a reasonable time in sociocultural terms.

(c) Non-discriminatory and acceptable solutions to fit normative criteria.
(d) Potential accessibility for all;
(e) Technically feasible solutions given the state of the art and modern techniques.

Technical and economic feasibility can be defined as a currently available ambient device useable by anyone, an ambient device that can be used with the help of an available technical aid or a personal technical aid. These questions help to avoid overlooking solutions that are based on universal design or claiming that full accessibility is unfeasible and settling for simply applying the norms and standard regulations.

In the context of this document we limit our considerations to the problems linked to the accessibility of transport systems for the visually impaired, which are the principal subject of our studies, but the principles involved may be extended directly to the accessibility of any public spaces or buildings.

2.1 Accessibility to Transport and Public Spaces

All European countries have a legislative framework and regulations to ensure minimum standards of accessibility for public spaces, new construction and transport infrastructure, but new initiatives have been launched over the last few years to improve standards in line with advances in technology and current political thinking. The law on accessibility which was introduced in France on the 11th of February 2005, aimed to achieve full accessibility for everybody by 2015, but despite important advances in many areas, not all the aims were met by the deadline, mainly due to the economic and practical difficulties involved and a revised programme has now been put into place.

Amongst the practical difficulties to overcome is the fact that improvements are particularly difficult to achieve for existing infrastructure and transport systems in older towns and cities where the installations are often more than a century old and there are problems in finding the space or the money to make the modifications required. In such cases it may be impossible to ensure complete accessibility for all and solutions such as alternative transport services may be necessary for some types of disability. Nevertheless, changes to improve accessibility in the existing infrastructure are achievable and would reduce the demands and expenses for alternative services. Any attempt to achieve progress in this area demands a minimum level of comprehension of traveller’s real needs and a corresponding system of verification with centres of expertise in order to ensure that the situation can be improved. With the introduction of new regulations and political initiatives, many regional or local authorities, transport, highway, civil engineering and building organisations have implemented public consultation procedures to diagnose the most critical problems, carry out experiments to define solutions and initiate work programmes based on the results. As participants in some of these investigations into public transport systems as presented for example in Pretorius et al. [3] and

Uzan et al. [4] we tried to formalise some of the problems faced by the traveller and identify some models that facilitate the understanding of the requirements to improve accessibility, particularly for the visually impaired. The results of these reflections have been formalised in the development of a model of accessibility called SOLID. This model breaks down all the principal elements, tasks actions and phases involved in entering and completing a journey in a public transport system and permits the analysis of problems and solutions or validates the accessibility for the disabled user [5, 6]. The essential elements of the model are briefly summarised in the following section and a detailed analysis and discussion of the practical aspects to identify problems and solutions in the context of the visually impaired user are treated later.

3 The Model SOLID

The name **SOLID** is an acronym of the first letters of the five essential elements involved in ensuring that any user has optimum parameters for accessibility to the transport system, enabling him to arrive safely at his destination. These elements are **S**afety, **O**rientation, **L**ocalisation, **I**nformation and **D**isplacements.

Safety

Ensuring the **S**afety and security for all the users in all circumstances and at all phases of the journey is of course the primary responsibility of any transport system. The design of the systems and infrastructure should ensure that travellers with any disability are catered for, both in terms of the man machine interfaces and providing solutions to resolve any problems of guidance, localisation, information and displacements to complete the journey. Special safety procedures put into place to any eventual mechanical, electrical or electronic failures should also be designed to cater for the disabled.

Orientation

The correct orientation of the traveller during the journey requires providing timely indications of the direction he should take at each stage in order to allow him to follow his route. The issue of orientation is closely linked to that of localisation for visually impaired travellers, since standard signs or display panels indicating the direction to follow to reach the appropriate train or platform are not adapted for VIPs.

Localisation

Localisation refers to the need for the user to know where he is and the direction of local points of interest at any given moment. Confirmation of progress by an indication of his arrival at appropriate “milestones” or intermediate destinations of the journey (ego-localisation) and the relative position of points of interest with respect to his current position (allo-localisation) should be provided using methods adapted to those with disabilities. For public transport systems, ego-localisation confirms that the traveller has reached the required entrance, intersection, ticket barrier, bus stop, station or platform. Allo-localisation indicates the relative position of other strategic points of interest from his current position, such as ticket offices, information displays, maps, stairs, escalators, lifts, toilets, entrances and exits and commercial installations.

Information

The information for the location and orientation of the traveller as well as the direction of points of interest is generally provided by standard signs and information panels. For the visually impaired the means of communicating information is necessarily limited to audible messages. For VIPs who also have difficulties walking or climbing stairs, information on the presence of alternative routes, enabling him to use an escalator or lift will also facilitate their journey. Information provided by these means of communication could include directions to more accessible routes, but will include train destinations, arrival times and perturbations or delays as well as commercial or tourist information.

Displacements

The displacements undertaken by the traveller will be actions linked to the essential tasks of entering and proceeding through the station, finding the correct platform and entering the train, riding to the destination and the process of leaving and the procedures to follow in case of an emergency. The displacements requiring the greatest physical effort will be the pedestrian phases and those requiring the least effort the phases of riding on an escalator or in a lift and riding in the train.

These five elements define the fundamental characteristics, tasks and information required to ensure a successful and safe journey in a transport system, but not how to facilitate the accessibility and ensure the completion of these tasks for a person with disabilities. In order to analyse the problems of accessibility faced by VIPs each task may be broken down into a sequence of sub-tasks to identify difficulties or requirements to complete each phase successfully. This is illustrated in the next section in the context of using the model to identify problems of accessibility encountered in existing transport systems.

4 General Principles and Problems for Accessible Public Transport

The traditional and often elegant entrances and information panels in older metro and underground systems such as the Parisian metro entrances shown in Fig. 1 illustrate the problems faced by VIPs when using existing systems. They need to be modified to meet modern accessibility standards and in particular, the presence of

Fig. 1 A traditional Parisian metro entrance and network information display for travellers

steps should be indicated and other forms of guidance should be available. Details of the lines destinations and network should be available using appropriate modes of communicating information.

In the next section we describe the basic elements of accessibility and explore the problems and general requirements of ensuring that physical constraints, human behaviour and different technical solutions may be taken into account. This constitutes a more complete approach to analyse, evaluate and validate practical solutions for the visually impaired in their context. Further discussions illustrate the impact of such an approach to characterise the influence of technological choices and methods of assisting this type of user.

The model of accessibility is constructed from a superposition of the four elements or phases that apply to each stage of the sequence of operations that are involved in defining a successful accessible design. The first two are,

(a) “Entering” a zone, building or public space, entering a lift, escalator, train carriage, bus, tram or any other form of transport
(b) “Actions” such as buying or using a ticket at a barrier, using a piece of equipment such as a ticket machine, finding the right platform, entering and finding a place in a carriage, lift or escalator and travelling to an intermediate destination etc…

These first two phases may be summarised as “entering” and subsequently completing an “action”,

Two other phases or elements remain which can be summarised as “exiting” or leaving after normal completion of the “action” and a final phase of providing a safe route for “evacuating” to a safe location in cases of emergency. The sequence of the different phases required to complete a given process is illustrated in Fig. 2. Experience shows that it is relatively easy to ensure that the processes of ensuring accessibility for entering and evacuation in an emergency are catered for,

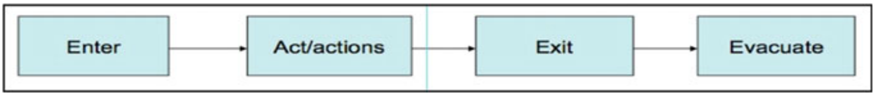

Fig. 2 The different phases involved in completing a task in an accessible environment

but the processes of completing one or several “actions” and “exiting” or “evacuating” without difficulty are often neglected or more difficult to assure for those with disabilities. The concept of providing interfaces to enable these “actions” to be completed without difficulties obliges architects, engineers and designers to adopt a common systematic approach to try to meet all the requirements of universal design to adapt the interfaces for all types of user.

The major differences between ensuring accessibility to electronic or digital interfaces on the one hand and mechanical, structural and physical spaces on the other, is the costs of updates, and the ease of implementing modifications that might be necessary to improve accessibility. A website or digital application is “live” because it is renewed frequently in the course of time, often several times a year, a month or a week and improvements can be made rapidly to counteract any problems encountered by users. Physical sites, such as buildings, equipment, transport infrastructure and rolling stock are difficult and expensive to update and are generally the object of relatively long term programmes of scheduled improvements or modifications over a period of 10, 20, 30 or even 40 years. The constraints associated with the preservation and conservation of physical assets, structures, machines and their renewal are also very different. The concept of physical accessibility, which is the basis for our model, has been developed after multiple studies and analysis of the needs and problems of disabled passengers using public transport and particularly those of the visually impaired. In this context the constraints of the site and the difficulties of carrying out improvements in a restricted space are major problems for management. The design and exploitation of systems of assistance and the validation of personal or general systems of aid and information for the voyager are crucial.

In a broader context the functional specifications and development of devices with Human Machine Interfaces adapted to providing assistance for localisation and guidance for visually impaired pedestrians in urban areas have been tested in many countries including France. As participants in these studies our analysis of the requirements for guidance, information, localisation of points of interest and transportation data (destinations, schedules, disruptions) resulted in a categorisation of requirements adapted to our local and national criteria. Different projects dealing with the different modes of transport and their associated areas included, bus stops in city streets, design of roads and shared spaces, trains and stations, metro and underground stations and systems of information for voyagers and tramway systems.

In these studies, different technologies of localisation were compared (GPS, wireless footprints, inertial navigation, visual landmarks and RF tags) and various associated interfaces (voice, visual) on personal devices (smartphones, remote controls) or ambient systems such visual displays or public address systems. The use of such devices does not however permit the basic concepts of providing an accessible environment to be neglected or ignored, so the description of the model of requirements provided by SOLID is a valuable tool in the process of analysing, designing and validating the functionality of solutions to improve accessibility.

It should be noted that people walking in the accessible areas in a public transport system often disregard signs or social codes and do not follow the rules such as keeping to the right or walking in the wrong direction even if they can see the signs. Travellers walking on the wrong side of the passageways, stopping without warning or slowing down and pushing past others are particularly hazardous for the visually impaired. For them, the level of concentration required to memorise and follow their route and detect potential clues on their environment is a significant effort under normal conditions and any antisocial behaviour of others can lead to the possibility of collisions with other travellers or falls, or at the very least a lapse in concentration and subsequent disorientation. It is therefore essential to remind users of the rules frequently and provide the means for the visually impaired to verify their position and other information. It is also particularly important that the name of the line, the current and next train or metro as well as the destination should be communicated by the public address system as well as visual displays to persons waiting on the platform or travelling in the train. Often, even if there is a vocal message there is no display for persons with problems of hearing and vice versa. Often the intelligibility of the public address system is inadequate, due to background noise, poor acoustics, poor message structure, or excessive speed of delivery. These kinds of problems are obviously being remedied as new rolling stock, infrastructure and communication systems are introduced to update existing lines.

4.1 The Chain of Mobility

The displacements of a person using public transport are a succession of phases where the user is either walking on or in stationary infrastructure or being transported and almost immobile in a moving vehicle, a lift or escalator. This can be represented by the chain of mobility, part of which is illustrated in Fig. 3 below. The transitions between the phases where the traveller is being transported are of course the most critical for those with mobility problems and this situation applies for any kind of disability but is more acute for wheelchair users or visually impaired, persons. Access to older transport networks including metro or underground systems is difficult for the former because of the physical barriers and lack of lifts and also for those who are visually impaired because of their need for guidance and information. These circumstances have a direct impact on vigilance, attention, susceptibility to stress and the priority of the need for information for a person who is visually impaired.

The traveller moves on a journey defined by alternating stages where he is walking and using all his faculties and concentration to find his way or travelling in

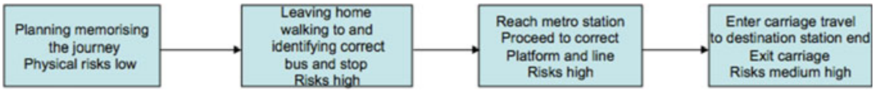

Fig. 3 Part of the chain of mobility when using the metro, train or bus systems

a vehicle where he can relax until he arrives at the next milestone on his journey. The journey represents the contents of a representational and semantic memory of the subject (a mental image of a map or itinerary) or the recollection of an external image (a map, network or neighbourhood, line etc.) before he lost his sight. He follows the route marked out by successive landmarks, each one in turn consisting of a goal or milestone (or an intermediate destination) and a point of exchange for new information (new beginning). Each milestone is a stage on the itinerary and thus a "mental switch" for the collection of information. It is a point of arrival and also a point for a new beginning. The mental attitude (cognitive and possibly affective) is different in terms of the treatment (e.g. verification of the landmark and then switching to the identification of a new segment of the route) with an effect on the emotions connected with the discovery or recognition of each new landmark on the itinerary. Waiting for a vehicle is not considered here as "immobility", but is part of the pedestrian's route which could be used for other integrated activities. Immobility is considered as a period of total inactivity where no further planning or preparation is involved such as the end of the journey.

4.2 *The Motives of the Journey*

The motives for undertaking a journey have a great influence on the strategy, planning and information requirements of any visually impaired person. Any journey involves going out into the street, walking and/or travelling to one or several destinations, eventually using public transport or other means of transport. Journeys that are regularly repeated are quickly memorised, are the easiest to learn and become routine without any stress. Others for pleasure often require planning, but unfamiliarity can lead to problems and the likelihood of errors or delays. These motives can be divided into five main categories, linked to the reasons, regularity and purpose of the journey:

(a) Going to work, school, university or shopping; a regular, often repeated route.
(b) Physical Activity, for example jogging, walking, walking the dog; frequently repeated routes
(c) Social relations with others, visiting family or friends, museums, theatres, art galleries, meeting out for coffee, lunch or tea; Irregular or rarely repeated variable routes
(d) To visit a stately home or gardens, a landmark or village in the countryside. One off visits

(e) To reach a place for vacations or meet with a person. Even if the destination is fixed, such as an apartment or hotel other persons are potentially mobile and could move during the journey, or be delayed, necessitating a change of the meeting point (a sporting event, the tour de France or a rally for example).

4.3 The Zones of Displacement

Articulated around the treatment of the information and tasks of the pedestrians, the zoning of the model does not exactly follow that derived from the functional organization of the station with its lines, shopping areas, or access zones to ticket machines, passageways, escalators, stairs, platforms and trains, but remains consistent with it:

(a) The zone at street level or main transit area is characterised by the diversity of potential configurations with multiple activities including commercial, cultural and residential activities one of which is transport so it is multifunctional. The pedestrians in this zone are not necessarily using the transport system.
(b) The access zone is where the main activity of the persons present is to move from the surface zone to the boarding zone or, conversely, from a train to the surface or street. This zone may or may not be dedicated specifically to transport. It can be crossed by a significant number of people shopping or travelling during the day and particularly by commuters hurrying to their destinations during rush hours.
(c) The transfer zone includes the platform in a station or tram stop, the curb or bus shelter at a bus stop and the entry and exit zones at the interior of vehicles, which are close to the entry and exit doors. It is destined for transfers during the arrival and the departure of the vehicle and the transfer of passengers from the platform to the seating zone of the vehicle and vice versa. This is an area where there is limited time to enter and leave because the bus or train has to close the doors and continue the journey. This can cause stress for persons with problems of mobility and is a zone where the need for security and guidance is a priority.
(d) The zone of "transportation" is inside the vehicle. In this area the traveller is relieved of the responsibility of walking and searching his way or exercising physical movements and delegates this task to the transport system. Cognitively, he is in a situation similar to that of waiting at a bus or tram stop, but is not expecting the arrival of a vehicle, simply the arrival of his vehicle at his destination.

5 Integration of Requirements Using the Model of Accessibility SOLID

The model takes into account each factor necessary to complete the journey successfully. In addition to the primary factors of safety, orientation, localisation, the acquisition of information and the means of displacement it is also necessary to analyse the chain of mobility, the motives for travelling and identify the phases of the journey which are difficult for the user with impaired mobility. In the case of persons who are visually impaired, the means available to enable him to guide himself in security are a fundamental part of the equation.

5.1 Design and Aids for Safety

As previously mentioned, the first and most important requirement for any public transport organisation is to ensure the safety of all travellers and members of staff at all times.

This can be ensured by designing the public areas to avoid any possibilities of accidents, presuming that we exclude any accidents due to failures of mechanical, electrical or electronic systems of the rolling stock and infrastructure. This requires optimal accessibility with ergonomic and logical design, minimising distances to be covered, direction changes and variations in level for those with any kind of disability. For those with disabilities, reliable systems to warn them of obstacles, inaccessible areas or potentially dangerous situations where they could trip up or fall are required.

These include stairways, escalators, lifts, corners or changes in direction or floor level. This is particularly important in congested platforms and passageways where collisions with other travellers may occur. This is of course vitally important for those who are visually impaired, since they will have difficulties choosing a clear pathway to avoid bumping into other travellers coming in the opposite direction as well as identifying any temporary or permanent obstacles on their route.

5.1.1 The White Cane

The standard tool used by the visually impaired for guidance and ensuring safety is the white cane, which is helpful for avoiding obstacles, but also indicates to fellow travellers that they should try to clear a path and avoid contact. The idea of a white cane originates from 1921 when James Biggs of Bristol, England decided to paint his walking stick white in order to make it easier for him to be identified by drivers when crossing the road. Campaigns to introduce the white cane as a symbol for the blind led to their adoption in France, England and the USA from 1931. After World War 2 Dr. Richard Hoover introduced the concept of the long white cane for

American soldiers who had lost their sight during the war. Up to this point VIPs held a white cane in front of them to warn others of their disability and to detect obstacles directly in their path. The new longer device enabled them to sweep the cane in front to detect obstacles, barriers, edges of walkways and changes in the surface at a greater distance. The greater length improved their visibility to others. It has since become the primary mobility tool for the visually impaired and is well adapted to most situations including travelling in public transport systems The main functions of the long cane may be summarised as follows;

(a) Identification to others of their disability
(b) To detect and explore around obstacles and identify their form and nature
(c) To detect boundaries and follow a path, passageway, corridor or a building or boundary wall
(d) To detect changes in level, gaps and negotiate stairways, doors and entrances
(e) To detect changes in surfaces, gravel, grass, holes, material and tactile paving characteristics
(f) An assistance to maintain equilibrium

A white cane provides a guide of the relative position of walls, stairways and obstacles, but it is not always spotted by other travellers, particularly those walking immediately in front of the user in the same direction or in spaces where there is cross traffic and the cane may contact their feet or legs. This kind of problem is generally well accepted by the passenger affected, but can sometimes cause difficulties. A hard prolonged contact may also permanently distort the cane, particularly if it is made of aluminium or a metallic alloy. For this reason, carbon fibre canes are preferable to the metallic versions, despite their increased weight, since they are not distorted in this kind of incident. Another alternative to the white cane is of course the guide dog, which performs a valuable role in ensuring safety for VIPs, but not enough persons are able to have one.

5.1.2 Tactile Surfaces

Tactile pavement surfaces were first introduced for pedestrian crossings in streets in 1965 by the Japanese engineer Seiichi Miyake. A regular pattern of flattened domes, cones or blisters are introduced in the paving at the edge of the footpath in order to help visually impaired pedestrians identify the boundary between the footpath and the road. The kerbs at pedestrian crossing areas are lowered to simplify passage for wheelchairs, push chairs and prams and the transition from the footpath to the road surface could then be detected by the visually impaired since this pattern could be detected when walking on it or with the help of a cane. The same principle was extended to warn of danger on the edge of platforms in train stations in Japan in the 1980s and later in Australia and other countries in Europe and elsewhere. Tactile paving surfaces are used to indicate any potential obstacles or other hazards wherever possible as well as for guidance and information, but standards vary from one country to another. Tactile paving is used at the edge of platforms and can be employed at the entrance to stairs, escalators and lifts and to warn of any changes in level. This tactile paving gives a visually impaired person a warning that they are entering a zone which could be dangerous or which warns of an impending change in level and can also be used as a guide to avoid obstacles. The lack of an international standard for tactile paving has led to inconsistencies between the applications and formats used in different countries.

Difficulties with identifying obstacles or changes in level may also be encountered by partially sighted persons who have problems such as macular degeneration, glaucoma, a restricted field of view or any other defect. They may still be able to visually identify zones of danger if these are indicated clearly. These persons will not necessarily use a long white cane to identify the surface in front of them, so may not detect the tactile paving before stepping directly on it, unless it is in a contrasting colour. The use of different colours and contrasting shades for tactile paving as well as their pattern depending on their function is a way of improving safety in such cases. Their use has been codified and adopted in national standards in Japan, Australia, Europe and many other countries. The use of white or yellow for tactile paving to contrast with grey bitumen or the lighter shades of tiled surfaces used in some station platforms, but other combinations of contrasting colours have also been adopted.

On the left of Fig. 4 below is a photograph of an overhead line metro station in Paris originally designed over a hundred years ago. This is typical of the design of stations of that period, which were implemented in many train, metro and underground systems in Europe and elsewhere. Following the introduction of tactile surfaces in France the edge of the platform is now indicated by a strip of white paint preceded by a grey tactile pavement warning surface with the standard pattern of raised domes. In the more recent metro system at Washington DC on the right of Fig. 4 the tactile paving is also grey, but red flashing lights are added as an extra warning.

The stations shown in Fig. 4 have relatively narrow platforms and machines, seats and other obstacles close to the inside wall of the platform. This could constitute a problem for visually impaired persons, who would normally try to stay close to the wall and as far as possible from the edge as they walk along the

Fig. 4 A traditional overhead metro station (*left*) and a metro station in Washington DC

platform. It can be noticed that the station on the left of the figure is on a line using pneumatic tyres rather than standard steel railway wheels. These have the advantage of providing a quieter and more comfortable ride with improved braking and acceleration and improve the audibility of station announcements when a train is arriving or leaving the station, so the use of tyres is a distinct advantage, but unfortunately the operating costs are higher. The access is a stairway at the far end of the platform, but many of these stations have now been equipped with an up escalator and/or a lift for those with mobility problems.

5.2 Other Risk Factors and Solutions

Partially sighted users may also suffer from other conditions such as impaired perception, vestibular imbalance, deficits of attention or other health problems. In this same context, poor lighting, visual illusions, unidentified sounds or their reflections, missing warning notices for temporary maintenance work, staircase and escalator maintenance, irregular surfaces and a lack of handrails on stairways can all complicate the problem of orientation and necessitate deviations and more physical effort with the consequent increased risk of falling.

A fall is of course far more dangerous than simply bumping into someone in a crowd, particularly if it occurs down steps or escalators, or even worse, from the platform onto the rails, but for the elderly or others who also have problems of equilibrium, any slight contact with another person or object could potentially result in a fall. Obstacles which have a mass, shape or material which might affect physical integrity such as walls, partitions, seats, machines for distributing drinks or snacks, posts, poles and pipes can also cause similar problems for the visually impaired as can items left unattended such as bags or luggage.

The effects of collisions with objects or obstacles differ in an important respect in that they do not constitute a conflict of interests between persons, since only the disabled person and the object or obstacle are involved. Avoiding the risk of collision with other persons may sometimes imply the resolution of conflicts between users and the risks related to security or the perceived risk of theft or assault. This is also the case for other emergency situations and any conflicts that might arise associated with the ability of the disabled user to evacuate rapidly to exits or safe areas in case of an incident, accident, fire or other emergency.

On the left side of Fig. 5 below, the first author, who is blind, is shown using a long cane in his left hand to negotiate a set of stairs at the entrance to a public building. For a partially sighted person a contrast in colour or shade between the risers and the horizontal floor and steps as you enter the building can help to identify the presence of stairs, but only the aluminium profile between the top of the riser and the step above is visible when exiting.

As an example of the use of tactile surfaces in this context, the photograph on the right of Fig. 5 shows a stairway in a metro station with a white tactile warning surface at the top of the steps to warn VIPs of the impending change in level.

A tactile surface warning strip is also present at the beginning of the second flight of steps. In other countries such as the UK the choice has been to use warning strips composed of parallel strips or a "corduroy pattern" at the top and bottom of stairways. The railings surrounding the stairwell permit the entrance to the stairwell to be easily identified with the aid of the cane and the handrails guide and help to support the user when climbing or descending the stairs. As previously mentioned, the user of the cane in Fig. 5 is left-handed which may also be a positive advantage when negotiating steps in metro systems where the convention is to keep to the right. The right hand may then be used to hold on to the handrail and the cane used to locate the position of the next step up or down. The cane is also used to identify the position of the train doors and any change in level or gap between the platform and the floor of the train. One of the primary dangers, that of falling from the platform onto the tracks, is gradually being dealt with in Paris as some older metro lines are being equipped with barriers between the platform and track with automatic synchronised doors that only open when the train is present and in some cases automatic driverless operation (see left of Fig. 6).

Fig. 5 Using a *white cane* (*left*) and a tactile warning surface (*right*) to identify the top of stairways

Fig. 6 French metro station with a new safety barrier (*left*) and guidance path in Spain

The tactile pavement and white paint strip at the platform edge have been removed with the installation of the barrier since there is no longer any risk of falling onto the track and the barrier constitutes a safe reference for the traveller to orientate his progress along the platform.

5.3 Orientation Requirements and Practical Solutions

Orientation is the second element of the model and refers to the ability of the traveller to be able to determine the direction he should take to reach his next intermediate destination or milestone. This entails following the route to each intermediate point, in the direction of the next milestone on the journey, without deviating. Orientation is of course only relevant once the traveller has been able to plan his route and verify his location at each phase and is the first information required at the beginning of the journey.

The problem of orientation is closely linked to the physical and mental capacities of the person making the journey particularly if he is unable to read signs and verify the direction he should take on the next phase of the journey. If the correct orientation is chosen at the beginning it is preferable to walk straight to the next milestone, however this is a difficult task for VIPs, since they cannot walk in a straight line without visual verification of their progress. VIPs negotiating a platform, a passageway or larger space usually use their white cane to locate the rear wall, sidewall or perimeter and follow this until the next intersection is encountered. As we have seen above, these walls are used for seating, vending machines, waste baskets or occupied by other travellers, which could lead to difficulties and conflict and it would be safer to walk in a straight line in the middle of the platform. In fact tests show that VIPs or blindfolded subjects unable to verify their direction of travel cannot walk in a straight path and the normal tendency is to walk in an approximate circle of greater or lesser magnitude [7]. Slight discrepancies in the symmetry of the human body have been suggested as possible causes, but this research showed that the direction of deviations or veering is closely correlated with the variations of the positions of the centres of pressure on the soles of the feet and that only 40% of the persons tested veered always in the same direction and none could walk consistently in a straight line. The conclusion of the research was that deviations from a straight line were triggered by vestibular inconsistencies, which were variable in time, rather than postural discrepancies.

The solution available to deal with this problem is the use of a different type of tactile paving to guide the traveller on the correct path. The Japanese introduction of tactile paving with a pattern of flattened domes or blisters was later followed by the development of another pattern for guidance using rectangular motifs to indicate the preferred path to follow [8]. This pattern is used in most public transport facilities in Japan, New Zealand, Australia the UK and other countries, but has not been universally accepted. The pattern used for this type of tactile paving is rectangular in form with the longer axis of the rectangles indicating the line to be followed. On the right of Fig. 6 is an example of the implementation of this system in Spain where path from the entrance is defined using the rectangular pattern paving on the right and the intersection with the path to the ticket office at the top of the photo and the path to the ticket barrier on the left is signalled using the warning dome pattern. The main objection this system in France is that the destination or direction of the guidance path is not indicated, so the user may be travelling the wrong way [9].

It does however permit improvements in maintaining the correct orientation and following a straighter path for blind and partially sighted users providing that information on orientation is available at each intersection.

The problem of indicating the correct direction to follow in station platforms in Japan by orienting the guiding surface obliquely from the train exit door in the direction of the exit before it joins the main guiding surface in the middle of the platform. This ensures that the visually impaired traveller can move along the platform without the risk of entering into contact with obstacles such as seats, vending machines and other obstructions, which will normally be located along the wall furthest from the rails.

One solution is the integration of RFID chips in the tactile paving such as that proposed by Kurachi et al. in Japan [10]. A cane equipped with sensors is used to read the information and indicate the direction followed as well as the location. Other systems of guidance and communication are being developed using wifi beacons, bluetooth location, light data transmission or other means in combination with tactile guidance paths as mentioned in [11]. The norms for tactile surfaces change from one country to another [12, 13], but blister heights (5 mm +), separation (50–70 mm) and dimensions 25–35 mm diameter are similar.

5.4 Route Planning and Learning

For VIPs it is necessary to commit all this information to memory before the start of the journey and/or ask for help along the way as required. If he wishes to learn how to use a new route which he will use regularly in the future to go to work, school or other destination, a guide is necessary to train him. Courses of "travel training" exist in most countries, alternatively friends or colleagues can help during this learning process.

During the course of a journey it is also necessary to purchase a ticket, pass through the ticket barrier, proceed to and find the correct platform and catch the correct train. Where trains on the same line have two or more alternative destinations it is important to be able to verify that the train is going in the direction you require. This information is normally shown on an illuminated display and broadcast on the public announcement system. For VIPs the only source of the information available is the public announcements, which can sometimes give incomplete information or be difficult to understand. Therefore advanced guidance systems, which could relay messages as well as position at the relevant time would be an extremely useful asset.

The use of a white cane can be discarded if a guide dog is available, but not all dogs can guide a VIP in the metro except on a regular journey and orientation and planning the journey is necessary in other cases. This is only a partial solution, but the other problem is the memorisation of the different phases of the journey, since knowing where to turn and taking the correct direction at every section of the journey requires a good memory or other source of information. The indication of where to turn can be provided by a personal guidance system at the intersections and retain details of milestones or points where his progress can be verified. He should also be able to find or choose an alternative route in case of need.

5.5 Information Delivery and Classification of Needs

Information is provided in response to needs. We can classify them into different categories for security, localisation and orientation, transport information and payment as well as information services related to physical displacements within the station. They may also be classified according to the requirement of being synchronised or not to the displacements. There is therefore:

(a) Structural information and synchronised updates on services lines, platforms and destinations;
(b) Cyclical information: linked to temporary situations such as maintenance work, holidays, and closure.
(c) Event information which is of short duration, a temporary interruption of traffic, a suspicious package or the arrival of a train.

The problems of defining the optimum timing and method of delivering information were initially defined for vocal interfaces to aid in the localisation and orientation of visually impaired travellers in bus interchanges or subway stations. Three key instants have been identified for the dissemination of information, at the entry of the traveller in a key zone, when there is a change of situation, such as the imminent arrival of a train and when there is an emergency or a change of platform or schedule The efficiency of the delivery of each type of information depends on the mode of communication used by the system and the physical and cognitive capacities of the traveller.

Sources of information such as access zones to transport, lines, destinations, routes, schedules, and disruptions of services have to be available to VIPs. Information on the environment and peripheral activities such as tourist attractions, landmarks, shopping facilities, entertainment and cultural centres would also be included. This could be provided by ambient installations, which give visual information and additional vocal information to those are affected by visual impairment. Often some of this information may be considered excessive or redundant for the everyday traveller, but may be essential for those with disabilities. In order to adopt a systematic approach to evaluating the different needs and types of information required to ensure optimum safety and guidance for all classes of user we have developed a model of the basic requirements and tasks involved when using public transport.

5.6 *Displacements*

Displacements constitute the final factor of the model, where the mobility and mode of progression of the traveller is linked to physical or cognitive difficulties he has in making his journey. Shared or large spaces constitute a difficult challenge [14–16] and tactile guidance paths and zone delineation provide a solution if used with modern localisation devices. The installations should be designed to avoid any difficulties or the obligation to cross barriers or paths with difficult accessibility. Means of avoiding problems should be provided by giving indications of alternative routes where the traveller has reduced mobility or has problems due to age, physical or cognitive impairments. Clear indications of the location of any elevators or escalators should be provided and the needs of travellers with other disabilities should also be taken into account [17, 18].

6 Conclusions

The increasing use of personal devices and ambient sources of information for orientation, localisation, and general information in combination with better design and the use of tactile surfaces has led to improved accessibility and greater facility for persons with problems of mobility to use public transport. The model SOLID helps to define the requirements to successfully define potential improvements or weaknesses in metro or train services and infrastructure. and analyse the different aspects causing particular problems Optimum solutions for accessibility can be investigated using this model in advance at the design stage or when specific changes are proposed to existing infrastructure. Since trains and buses are designed to be used for many years, it will inevitably take a long time to completely replace older stock, which will not be to the latest norms. It is also difficult or too expensive to find space to guarantee step free access in all the older metro or underground stations and therefore some lines will only have this feature at a limited number of stations which should be identified for travellers who need it.

In circumstances where existing outdated transport systems are being updated by transport authorities to comply with the new regulations, alternative transport solutions such as on-demand electric vehicles could be proposed to circumvent some of the problems, but much can still be done to improve accessibility in existing systems. The advantages of using this model are illustrated by the analysis of requirements for ensuring optimum mobility and accessibility in metro and train systems for the visually impaired, but the same principles can be applied to analyse the needs of persons with other kinds of impairment. Investigations are continuing in these areas, including the simulation of different sites to validate accessibility in wheelchairs, improving portable guidance and communication devices to take into account the specific characteristics of the user and testing and optimisation of vocal and visual communication and haptic interfaces.

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Part IV
ICT Technologies and Mobility

Mobility Technologies for Blind, Partially Sighted and Deafblind People: Design Issues

M.A. Hersh

1 Introduction

There are an estimated 285 million visually impaired people globally, with 39 million of them blind [75]. Blind and many partial-sighted people require travel aids and/or personal assistance to travel safely and reach their destinations, though the design requirements of partially sighted people may be different from those of blind people. Despite nearly 120 years of the development of electronic travel aids, resulting in a large number of prototypes and a much smaller number of commercialised devices, the most commonly used travel aids are still the long cane followed by the guide dog. Nearly 10% of the estimated 1.1 million blind people in the USA use a long cane and just under 1% a guide dog [83]. Since these are the two most commonly used mobility devices, this indicates that the majority of blind people in the USA and probably the rest of the world do not use any mobility devices. This is probably not due to lack of need and research indicates that there is still significant stigma associated with blindness and long cane use and that this may delay or prevent decisions to use a long cane [36, 37]. Two-thirds of cane users, but only one third of visually impaired people are below 65 years of age [21]. This indicates both the greater difficulties older people have in adapting to blindness and learning to use a cane and the need to take into account age and, in particular, the needs of older blind people when designing mobility devices. Surveys indicate that a significant minority of blind people do not leave the home (on their own) and those who travel on their own tend to travel locally and/or stick to known routes [14, 19, 31, 47]. While these surveys are dated and there may have been some improvement, this does indicate the barriers experienced by many blind people and the need for accessible environments and well-designed mobility aids to overcome them.

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There are a number of different reasons for the low usage of mobility devices other than the long cane and guide dog including [45, 79] high costs, limited (additional) benefits relative to the long cane, lack of easily available, low cost training and the difficulties involved in learning to use these devices, weight, unattractive and obtrusive appearance and lack of information about what is available. This can be summarised as insufficient additional benefits relative to the long cane to outweigh the additional costs and training required. Some of these devices are also affected by weather and other conditions, leading to inconsistent feedback, may produce disorientation from excessive sound information, involve cumbersome hardware, which is not easily portable and neglect social aspects of device use [9]. It has also been suggested [9] that devices should present an integrated, multifunctional, transparent and extensible solution. Although good design cannot be guaranteed to ensure the success of a new device, paying attention to design will lead to a better device that is more likely to be used by a significant number of people.

In the remainder of this chapter, the term ‘blind people’ will be used to refer to anyone with some degree of visual impairment, particularly, if they experience barriers to mobility as a result. Where it is necessary to make distinctions additional terms, such as partially sighted or deafblind will be used. It will be clear from the context whether the term ‘blind’ is being used generically or to refer to people who are legally blind, have light perception or are totally blind.

2 Preliminary Considerations

2.1 The Long Cane

Before the more general discussion it is useful to examine the main features of the long cane and the factors that have led to its relative success. Despite its limitations, which will be discussed below, the long cane is able to provide safe mobility to blind people who have had appropriate training, though additional aids and/or training will generally be required for travel in unfamiliar areas. It can be divided into the grip, a rigid or non-rigid shaft and the tip [93]. It is available in different materials, including aluminium, fibreglass and carbon fibre, with the most appropriate material often depending on the user and the type of journey [82]. The cane is light, though extended use can lead to arm fatigue. The simple mechanical design means that there are no moving parts or electronic components to malfunction. Although damage in use is possible, for instance through contact with vehicles, most modern canes are both flexible and robust and can survive a range of mishaps. The tip and the ties holding the sections together can be easily replaced if damaged, thereby extending the cane’s life.

The cane can also to some extent be customised to the user, with the option of different tips, folding, telescopic or rigid shaft, different handle design and various materials, with different weights and properties. There are also versions designed to be used in the mountains and shorter versions intended mainly to indicate that the user is blind. The cost is low enough to enable many users to have more than one cane, for instance to choose different canes in different contexts, and for a spare to always be available in the case of damage to the main cane. The cane takes up little space and can be left in a corner or folded up and put in a drawer or backpack when not in use. In addition to its function as a mobility aid for detecting obstacles, the long cane also acts as an indicator that the user is blind. This is advantageous to many users, enables them to obtain assistance and indicates to other people the need to give the approaching blind pedestrian extra space. However, the distinctiveness of the cane and its symbolic association with blindness are also seen as stigmatising by many potential users. Further drawbacks include incomplete protection against drop-offs, lack information about objects at a height and insufficient reach to provide much distance information or object and foot placement preview [83]. The cane may also get caught or stuck in uneven or irregular ground and has no way of detecting objects approaching at speed, such as balls or vehicles [64], though the latter are likely to be heard. Using a long cane safely and effectively is not easy and generally requires an extended period of training.

In summary the long cane is able to support blind people to travel safely, is low cost and robust. However, it has limitations, particularly, the need for extensive training to use it safely and the lack of information on high-up obstacles and beyond the reach of the cane.

2.2 Understanding How Blind People Travel

In order to design effective mobility devices it is useful to have some understanding of how blind people travel. The information presented here provides a brief overview rather than an indepth consideration of all the important issues. Mobility requires the analysis of sensory information to determine a direction of travel, avoid obstacles and move in a (relatively) straight line rather than veering. The travel may be to or without a destination, for instance, when exploring an area or walking for pleasure, though blind people generally travel to a specific destination rather than walk for pleasure. Unlike sighted people, who rely largely on vision for spatial information, blind people use information from all their senses with auditory and tactile information generally the most important. However, partially sighted people mainly use vision [35]. The different properties of the different senses (see Table 1) [44, 79] mean that blind people generally lack preview and overview information when travelling. Consequently, they need more frequent landmarks than sighted people to check that they are on the correct route.

Blind people generally use some combination of auditory, tactile, olefactory, proprioceptive and kinaesthetic information, with auditory and tactile information generally the most important. Objects need to be relatively close to the person to be perceived by touch, whether by contact with the cane, feet or hands or a combination of them. This means they act as either landmarks or obstacles or both

Table 1 Comparison of information from the different senses (adapted from [44])

Property	Vision	Touch	Hearing	Smell
Landmark info	Do not vary with time of day or season		Varies with time of day or season	
Focus	Sharp	Sharp	Less sharp	Less sharp
Spatial field	Large	Small	Large	Large
Object location	Precise	Precise within small field	Less precise than vision	Less precise than vision
Overview information	Yes, many signals at once	No, field is too small field	No, signals interfere with each other	No, signals may interfere with each other
Object identification	Good	Less precise than vision	Less easy than vision	Very imprecise

simultaneously and may change roles during a journey [35]. The lack of overview and preview information available to blind people [35, 44, 78] makes route learning particularly important. This enables them to use remembered knowledge about the route in an analogous way to the use of preview and overview information by sighted people. However, this memorisation involves a heavy cognitive load and the significant cognitive demands associated with concentrating on non-visual information may act to limit the amount of information it is feasible to remember. In addition, these factors in combination can mean that travel is very tiring for blind people and involves a lot of concentration.

Blind people use shore lines, such as kerbs, the edge of grass verges and walls, which are detected by the (long) cane in order to walk in a straight line. There is often a relationship between the particular mobility aid used and the available information. For instance, a blind person using a long cane will obtain obstacle and shore line information from the cane and can use this information as landmarks, while also needing to avoid the obstacles. Guide dog users will probably be unaware of obstacles which the dog guides them round and shore lines, since the dog may walk in the middle of the pavement. They will therefore need to use other types of landmarks. Consideration should be given to the information provided and its likely impact on travel strategies when designing travel aids.

2.3 *Categorisation of Travel Aids*

There are a number of different categorisations of travel aids, including the following [45]:

1. Into primary and secondary aids: Primary aids are used on their own to deliver safe mobility and largely involve detection of low-level obstacles on the path in front of the user, for instance the long cane. Secondary aids are unable to

provide safe mobility on their own and are generally used to supplement primary aids, generally by detecting obstacles, for instance at a height or a greater distance than available with the long cane.

2. Device functionality, including:
    a. Mobility devices for obstacle avoidance and/or detecting objects at a height, distance preview and/or detecting drop-offs
    b. Orientation and navigation devices that provide information on landmarks and support route finding
    c. Environmental access assistive technology
    d. Object location devices
    e. Apps, including for contextual information, real time timetable and other travel information and locating bus stops and other facilities.
3. The main technology used to obtain the environmental information, including ultrasonic, infrared, camera, satellites (global positioning system GPS), mobile phone technology and a combination of different sensors.
4. The way information is provided to the user:
    a. Tactile: vibration; Braille; other
    b. Speech
    c. Non-speech sounds: musical tones, sounds of varying loudness and pitch; virtual sound.
5. How the device is worn or carried
    a. Hand-held: cane; other hand-held device
    b. Carried: In a pocket or backpack
    c. Worn: on head; on body.

3 Overview of Travel Aid Development

3.1 Phase 1: Obstacle Avoidance Devices

The development of electronic travel aids has taken place in a number of phases [79], though there is some overlap between them and first and second phase developments are still continuing. The first phase focused on resolving the limitations of the long cane by detecting obstacles at a height and/or a greater distance to allow preview, frequently by either a small box clipped to the cane or a long cane with integrated additional features. From the design perspective there are probably advantages in the detachable box, as long as it is securely fastened, rather than the modified cane approach. If the additional components malfunction the box can be sent for repair, leaving the user with a basic long cane. If damage occurs to the mechanical cane, repair (or replacement) of a standard long cane is likely to be considerably cheaper and quicker than that of a modified cane and the user can transfer the box to another cane. In addition, the detachable box approach gives users greater flexibility by enabling them to use the additional features with the long cane of their choice or different long canes in different conditions. Examples include the laser cane [45], the smart cane [90], the ultracane [49] and the Tom Pouce and Télétact [24]. An overview of some of the obstacle detection devices is given in Table 2.

These canes all use infrared, ultrasonic and/or laser sensors to obtain environmental information. The different types of sensors are discussed in slightly more detail in Sect. 5.3. Most of the cane extension devices have used tactile or auditory interfaces to provide information to users, with tactile information generally

Table 2 Overview of obstacle detection devices [45]

Device name	Approx. year	Technology	Body position	References and notes	Current availability
Sonicguide	ca 1965	Ultrasonic	Head worn	[52, 59, 60]	Discontinued
Bat K sonar cane	ca 1965	Ultrasonic	Clips onto long cane	[90]	Commercially available
Pathsounder	ca 1966	Ultrasonic	Neck worn	[85]	Not available
Mims device	ca 1970	Infrared light	Head worn	[68]	Prototype only
Mowat sensor	ca 1970	Ultrasonic	Hand-held, torch-like	See [25]	Not known
Laser Cane™	ca 1970	Infrared system	Hand-held cane	[7, 8, 70]	Commercially available
Polaron	ca 1980	Ultrasonic and ranging (sonar) system	Hand-held torch format or worn on chest	[70]	Commercially available
Sensory 6	ca 1980	Ultrasonic and ranging (sonar) system	Head worn	[25]	Custom orders
Wheelchair Pathfinder	ca 1980	Ultrasonic and Infrared systems	Wheelchair mounted	[70]	Commercially available
Sonic Pathfinder	ca 1990	Ultrasonic	Head worn	[25, 46]	Not known
Ultra Cane™	ca 1990	Ultrasonic	Hand-held cane	[50, 91]	Commercially available
Tom Pouce	ca 1990	Infrared system	Cane mounted	[24]	Commercially available
Teletact	ca 1990	Infrared system	Hand-held/Cane mounted	[24]	Commercially available
Miniguide	ca 1998	Ultrasonic	Hand-held	[26, 27]	Commercially available

vibratory and auditory information involving possibly musical sounds of different frequencies. However, a number of these devices have paid insufficient attention to the difficulties related to the cognitive processing of complex information and the importance of not impeding access to environmental sounds, which are vital for the successful mobility of blind people. Successful use of devices presenting highly complex information will frequently require an extensive training period, but in many cases training has not been available, with the exceptions including the Tom Pouce and Télétact [24].

A more intuitive interface is provided by robotic devices, such as the GuideCane [92], which has not gone beyond the prototype stage. They contain a (small) motor and power source, enabling them to move to avoid obstacles. The user feels this movement through the handle and automatically moves to follow it. This gives an intuitive and easy to use obstacle avoidance system which does not require extensive training. This could enable some people who only go out accompanied to travel on their own at, least on some routes. However, the disadvantage of this intuitive interface is that users do not receive any information about landmarks or obstacles. They may therefore also require a basic wayfinding or navigation device, either integrated into the robotic cane or stand alone, to make up for the lack of landmarks, enable them to have some idea of their location and verify they are on the correct route. Drawbacks of the GuideCane, though not necessarily other robotic devices, are its unattractive appearance, difficulties in using it on stairs and the unsuitability due to the cumbersome design for use as a long cane in the case of malfunction of the robotic features. Another cane extension device which has links to the third phase (see Sect. 3.3) involves an attachment to the cane for ultrasonic sensors audio and haptic output via an android app on a smartphone [64].

3.2 Phase 2: Navigation and Wayfinding Devices

Navigation and wayfinding devices were the focus of the second phase and require the location of either the user or a particular point in the environment. This led to the development of two distinct approaches with overlapping functionality [41]:

- Global navigation satellite systems (GNSS), currently most commonly using global positioning systems (GPS), which locate the user.
- Environmental information beacons, which locate a point in space.

Both approaches can be used for outdoor navigation, but GNSS/GPS cannot be used indoors. It requires a line of sight signal which can be disrupted or completely obscured by tall buildings and dense foliage [30]. Since GNSS/GPS uses existing satellite systems the end-user needs a receiver, but no transmitters embedded in the environment or other environmental modifications are required. Beacons require a transmitter and possibly other hardware to be installed in the environment. This is a disadvantage, as it means that the user cannot control system availability and is dependent on the installation of transmitters and possibly other hardware. The provision of comprehensible information by GPS systems is dependent on the availability of maps of the area, for instance to enable information to be linked to particular streets and feasible turns to be indicated. Geographical information systems (GIS) can provide useful environmental information in navigation aids [58], but need to provide additional information for blind people, including on streets, pavements, junctions and marked paths across the road [28]. GPS systems for blind people include both stand-alone devices, such as the Trekker Breeze, Trekker GPS, Navigator and Kapten and software, such as Wayfinder, that can be used on a mobile phone or other mobile device. Both types of systems may provide additional functions. GPS systems generally provide information on points of interest and the location of facilities, for instance all restaurants within a certain distance of the user. The system can then guide the user to the chosen restaurant or other facility. Some environmental information beacons provide information about buildings or send signals to request vehicle doors are opened or the presence of an assistant. It has been suggested that guidance should combine orientation and localisation and provide warnings and information about the location of destinations, junctions and paths across roads, as well as orientation, progression and route-ending instructions, with a high degree of precision in all cases [28].

Environmental information beacons and most satellite navigation systems use speech to provide information, though some GPS systems, such as BrailleNote GPS, use Braille, generally as well as speech. The widest range of options is available in English, but examples in other languages include the Polish Navigator and the Czech system of environmental information beacons. The Talking Signs system [10] uses an infrared signal to transmit a repeating, directionally selective voice message from the sign to a hand-held receiver some distance away. The message becomes louder as the user approaches, helping them locate the facility indicated by the sign. The beacon approach could provide information about several different facilities located within a certain area of predetermined size around the user [53].

There are also a few aids which combine obstacle avoidance and wayfinding/navigation functionality. The Stick for Environment ExplorationS (SEES system, [96], Fig. 4) is a long cane-based device which combines satellite-based GPS navigation with obstacle avoidance information from a camera. It can also provide contextual information, such as the location of the nearest traffic lights.

3.3 *Phase Three: Apps for Smart Mobile Devices*

The third or current phase of development involves apps for smart mobile devices [56]. There seems to have been a natural progression from mainly hardware (phase one), through a combination of hardware and software (phase two) to purely software (phase three) with the hardware provided by an existing mobile device. Developments in information and communication technology (ICT), which have significantly increased the computing power that can be contained on small mobile devices, have enabled the move to apps. Currently, mobility related apps are used for very specific applications or provide very specific contextual information. A number of different apps have been developed, but the potential to provide a wide ranging navigation and information system has not yet been met. Design issues for mobile apps will be discussed in Sect. 4.4.

4 General Design Issues

4.1 Evidence from Device Acceptance and Rejection

In addition to travel aids designed specifically for blind people, there are also devices for the general population which could be used by blind people if appropriately designed. An example is the increasingly popular travel apps on smart phones and other mobile devices. Travel aids for blind people therefore have features in common with both other types of assistive technology and general purpose (consumer) products. Therefore, good design practice for the design of general purpose (consumer) products is also relevant to mobility devices.

Several studies have been carried out of end-user preferences for assistive technology features. The factors found to be the most important included effectiveness/functionality, costs of purchase (maintenance and repair), ease of use, durability/reliability, simplicity, appearance, safety features, ease of repair, comfort, portability and good instructions [6, 13, 94]. It should be noted that these factors are not specific to the design of assistive devices and can be considered to be general good design practice. There are also several studies of device use and abandonment, but most of them have focused on the devices used by physically disabled people. The results suggest that devices are most likely to be abandoned either in the first year or after five years. Abandonment in the first year probably implies that users either never really used the device in the first place or were only requiring or intending to use it for a short period to manage a short-term impairment or period of ill health, whereas abandonment after five years probably indicates a change in the user's condition or circumstances after an extended period of use.

The main factors relating to device abandonment for a sample of mainly physically disabled people were found to be user opinions not being taken into account in device selection, easy device procurement and poor device performance, reliability, ease of use, safety, durability and comfort, as well as changes in user lifestyle, activities, conditions, needs or priorities, including lifestyle and activity changes and changes in users' conditions. However, lack of information and support may have contributed to poor ease of use [77]. Like other assistive devices, mobility aids can be considered positively as an aid to independent living and increased functionality or negatively as a symbol of lost functionality [29] and disability status. This is borne out in a recent study of cane use by older people [37]. While it is important to challenge negative stereotypes of disability and the marginalisation of disabled people, this is a much wider issue. However, designers can design assistive devices to be as attractive as possible and to look like a device suitable for and attractive to the general population rather than something that only disabled people who have no choice about the matter will use.

A number of factors have been found to affect cane use by older blind people and are summarised in Table 3 [37]. In practice most of them will also affect cane use by younger people and the use of mobility devices in general by users of all ages.

4.2 Design Considerations

When designing mobility (and other) devices, designers should take into account the particular end-users they are designing for and the skills they will need to use the device effectively. This includes both general orientation and mobility skills and the specific skills required to use the device. An associated issue is the need for training [83]. While ease of use with a minimal need for training and minimal mobility skills has a number of advantages, in some cases there may be tradeoffs between device features and the skills and training required to use it effectively and safely. On the one hand, mobility devices have an important role in enabling travel by blind people, potentially including those with poor mobility skills who rarely if at all go out on their own. On the other, this raises the ethical and practical issues of the safety of blind people with limited mobility skills in the event of device malfunction or batteries running down. It is still an open question as to whether it is feasible to develop mobility devices which are sufficiently reliable and have appropriate functionality and performance to allow blind people to depend on them in the same way as on a sighted guide.

4.3 Principles of Good Design Practice

A number of principles of good design practice are listed below [3, 42] and several of them will be discussed in more detail in later sections.

End-user factors

1. User-centred design: involvement of end-users from the very start and throughout the design and development (and distribution) process [23].
2. Target end-users: awareness of the characteristics of the end-user groups the device is being aimed at and essential and desirable end-user skills in order to use the device safety and effectively.
3. Ease and intuitiveness of use: preferably without requiring extensive documentation and training and high levels of existing end-user skills. There may be tradeoffs between ease and intuitiveness of use and the features provided or more advanced features may require additional documentation and training and higher levels of user skills.

Table 3 Factors that affect cane use [37]

	Category	Encourage cane use	Discourage cane use
Internal	Self image	Positive self-image	Negative self-image in general and/or as a blind or disabled person
		Successful transition of self-perception from sighted to blind	Still has a self-perception as sighted
	Impacts of stigma	Not worried about what other people might think	Concerns about what other people might think, particularly those who knew them when they were sighted
		Reduced shame and embarrassment due to familiarity	Feelings of shame and embarrassment
	Equation of cane and blindness		Belief that cane use is only for totally blind people
	Attitudes to (in) dependence	Desire for independence	Acceptance of dependence and overprotection
	Safety	Concerns about their own and/or their children's safety, possibly following accidents or their close avoidance	
External	Societal attitudes to blindness and disability		Negative attitudes to blind and other disabled people
			Equation of blindness and cane use as a symbol of blindness
	Attitudes and behaviour of friends and family		Lack of acceptance and/or embarrassment of friends and relatives
		Support and encouragement from friends, family to use a cane and/or do things themselves	(Over)protection by other people and discouragement from going out on their own and/or doing things themselves
		Lack of availability of other people to accompany them and do things for them	Other people do everything for them
	Safety		Experience of being targeted for abuse due to the visible symbol of blindness
	Facilities		Lack of facilities in villages acting as a disincentive to going out
	Training	Availability of O&M instructors or experienced blind people to teach or help and support them	

4. Where feasible devices should be designed to minimise the required skills to enable them to be used by as wide a range of users as possible. In practice, this is unlikely to be feasible for more complex devices. It is also desirable that all device users have some level of mobility skills so they can manage in the case of device malfunction.

Functionality and features:

5. Functionality: specific clearly identified function(s) which are of value to users and fit into their lifestyles.
6. Appearance and portability: attractive, unobtrusive and/or similar to commonly used devices, light weight, easily portable. In considering the maximum weight the fact that the user may need to carry other items, such as shopping or tools, books and papers for their work or studies, should be considered.
7. Hands free use: hands free use is desirable to free the hands for other activities, such as using a cane and carrying baggage. If this is not possible use should require at most one hand.
8. Good performance: the device performs well under a range of conditions.
9. Reliability, durability, comfort and safety: blind users require devices to travel safely to their destinations. Device malfunction can leave users lost in an unfamiliar location. In the case of devices which provide obstacle avoidance functions, the option to use the device as a long cane in the event of malfunction is desirable.
10. Low cost: this should cover purchase, maintenance, repair and upgrade to make the device affordable. While small cost increases with increasing functionality may be acceptable, low cost design is important to avoid unnecessary barriers to device use.
11. Privacy management system: the importance of privacy and privacy management is discussed in Sect. 5.4.
12. Language: text and speech interfaces should be available in a variety of languages.

Design approach

13. Iterative, multi-criteria approaches: consideration of diverse factors including function, form, attractiveness to all the senses, pleasure in use, usability, accessibility, performance, reliability, safety and environmental factors. The frameworks for taking into account important design factors include the Promise Project’s six As: awareness, accessibility, availability, appropriateness (usefulness), affordability and acceptability [16].
14. Design for ease of upgrading, repair and maintenance: robust design to reduce the likelihood of faults occurring. This benefits end-users and the environment and could reduce costs.
15. A modular software architecture: this facilitates later developments, e.g. the addition of other functions and reduces the impact of problems in one component on other parts of the design.

16. Compliance with relevant standards or other regulations: good design practice generally goes beyond minimal compliance. Proactive rather than reactive compliance generally reduces costs.
17. Compatibility with the long cane (if the device does not provide similar functionality).

Information and training

18. Necessary skills and training: clear communication of the essential and desirable skills and required training to use devices safely and effectively and their relationship to existing skills, so that potential end-users can make appropriate choices about devices.
19. Documentation: the provision of appropriate information using clear language and layout and availability in a range of alternative formats, with at least electronic versions available in different languages.
20. Training: availability of suitable training locally for users with a wide range of orientation and mobility skills, preferably free or at low cost.
21. Follow-up: the availability of follow-up information, support, maintenance and repair facilities to end-users.

4.4 App Design

Mobility apps are equally relevant to disabled and non-disabled people, particularly in unfamiliar, complex and unstructured environments and when using public transport. Many apps, such as Find my bus or Find my bustop, provide information of relevance to both blind and sighted people. If designed to be compatible with a range of different interface modalities they can be used by both groups. Some mobility support devices developed for non-disabled people may have particular applications for disabled people. For instance, a smart travel alarm [69], which provides an alert when the user reaches a particular location, could be set to indicate when a blind user was approaching their bus or tram stop or railway station, with the time in advance chosen to allow them sufficient time to get off without haste. However, not all features are of interest to both disabled and non-disabled people. Facilities likely to be of interest to both groups include (i) personalised and contextual travel advice and information; (ii) route planning; (iii) navigation and wayfinding; and (iv) facility location; whereas (v) obstacle avoidance is particularly relevant to blind and some other groups of disabled travellers.

Blind people frequently also require both different types of information and more specific information than sighted people, for instance to turn left at a particular auditory or tactile landmark after walking two blocks rather than after the distance of 500 m without any other information [18]. They may also require additional information to walk these two blocks, for instance about the ground surface, the best shore line to use and where to cross the intervening roads. When going to the theatre information about the nearest bus stop and bus times for a particular facility is of interest to both blind and sighted people, though sighted people are more likely to have their own transport. However, blind people may also require detailed information about the route from the bus stop to the theatre entrance, including information about landmarks/obstacles, crossing points and the exact location of the entrance, whether it is approached by steps or a ramp or is level with the ground. They may also be interested in a live guidance/navigation feature and will want to know whether and, if so, for what performances audio description is available. They will also probably require text or audio descriptions of the theatre and an in-building guidance feature or otherwise require assistance in finding their way around the theatre. All these features could be provided by apps.

Apps have a number of benefits and considerable potential for (blind) end-users, both on a stand-alone basis and in conjunction with appropriate hardware. They use an existing device, with frequently minimal additional costs for downloading the app software. Many apps are open source or otherwise cost free, whereas others are commercially available for a relatively small fee. A single mobile device is able to provide a wide range of different functions through the use of different apps, therefore reducing the number of devices the user needs to carry around with them to obtain this functionality. Apps have the further very significant advantage for blind people of using a mobile device, such as a smart phone, which is used by the non-disabled population. Consequently, unlike some other travel aids, app use is not stigmatising. Apps are able to provide a range of contextual functions which take account of location awareness [71], as well as to allow information sharing between users. Context awareness is discussed briefly in Sect. 5.5. This means that app design should facilitate information sharing and the incorporation of the information received in contextual functions. However, as discussed below, improvements to the user interface will be required.

Apps on mobile devices could be used, probably together with appropriate hardware, to provide improved obstacle avoidance systems in combination with additional functions. A suitable user interface could be provided on the mobile device, but it is still open to question whether the incorporated sensors would be able to provide sufficient and appropriate information or whether additional hardware would be required. Such a device would be able to provide environmental and contextual information. However, as in the case of cane extension devices, it would probably need to be used in conjunction with the long cane. While having the advantages of additional flexibility and functionality, this would reduce the advantage of the approach of only requiring a mobile device and not using a potentially stigmatising additional ‘assistive’ travel aid.

By definition mobility apps are intended to be used while the user is mobile. However, the small size and multi-functionality that make mobile devices attractive by making them easily portable and enabling them to be used at any time and place make them more difficult to use, particularly, when the user is moving. Mobility and small size lead to reduced memory and processing speed, and the need for batteries to be regularly recharged [62], as well as small, relatively difficult to see or feel screens, keyboards and pointers. Other drawbacks which complicate mobile use and may reduce usability include limited, slow and unreliable connectivity, the need for some proficiency in data entry and limited input (and output) modalities [34, 97]. Small screens with low resolution can cause particular problems for partially sighted people.

Using mobile devices while walking can add to cognitive load [34]. This may be a particular issue for blind people due to the heavy cognitive load involved in their travel, as discussed in Sect. 2.2, as well as the need to memorise the location of controls on the touch screen interface. While accessibility features such as reading aloud the labels of buttons and other items when the user taps them are useful, they do not fully resolve this problem. The user still needs to be able to memorise the approximate screen layout in order to reduce time searching. The ability to use a keyboard or switch interface with mobile devices, offered by android and iOS platforms, is probably more useful. However, there is still a need for the design of mobile devices which have a range of input and output modalities without or with only minimal increase in size. The extra complexity and cognitive load associated with device use by blind people makes effective app design to facilitate ease of use particularly important. Apps need to be easy to both learn how to use and remember how to use when not used for a period.

A number of mobile apps provide navigation and wayfinding functions and consequently require the localisation of either the user or a point in space [41]. Mobile devices generally localise the user. This raises ethical issues related to the user's privacy and security and, in particular, who has access to this information and the measures required to prevent unauthorised access. This will be discussed further in Sect. 5.4. Options for localising the user include the use of a camera, Bluetooth and near-field communication or radio frequency identification (RFID) with environmental markers [57]. Camera-based approaches have the significant advantage of not requiring environmental markers, which may not be available, but the significant disadvantage of requiring the camera to be focused in order to take photos. This is not necessarily easy for blind people.

Mobile apps have been classified according to whether they run on the device's operating system (native), use a browser on a mobile device (web based) or use a common code base for native like apps on a wide range of platforms (hybrid) [54], Rudolph, undated). The choice of native or hybrid platforms is an important one, which generally depends on the complexity and type of application. Native apps may have advantages when development costs are not an issue and better user experience or device specific features are required. Hybrid apps have the advantages of allowing developers to use existing web skills and some device and operating system features. They have reduced development time and costs, a single code base for multiple platforms and easy design for various form factors, including tablets. Many developers prefer to develop native apps, which allow them to use device features, such as camera and sensors, and avoid the problems of poor device connectivity, since the app is not web based. A number of developers have been found to prefer open source platforms, whereas others are concerned about the lack of adherence to standards that can result [54].

5 Design Features

5.1 Device Functionality

One of the important choices that influence many other aspects of the design is what functions the device provides. The overview of the history of the development of mobility devices in Sect. 3 shows a progression from obstacle avoidance devices, through navigation and wayfinding devices, possibly with additional features, to apps able to provide a range of possibly contextual and smart functions. Navigation devices based on GPS are able to provide information about points of interest and other location specific information. Wayfinding devices based on environmental information beacons are able to guide users to a particular facility and provide information about it. They may also offer options for requesting assistance, opening the doors of public transport vehicles and turning on audio pedestrian crossing indicators. Different approaches are frequently taken to navigation indoors and outdoors. In particular, satellite systems do not function indoors and indoor systems are of the environmental information beacon type based on the RFID or infrared tags. The nature of indoor environments also means that they may require a relatively high density of tags, e.g. one every few doors.

Other functions of interest include reading street names and numbers and information boards, informing the user of their current location, finding pedestrian crossings, bus stops and other facilities, identifying the building or feature in front of the person and providing information about it, locating objects in various contexts, including goods in shops, indicating the user's public transport stop or station, and providing audio information about the status of traffic lights, i.e. whether the lights are indicating it is safe to cross the road [40]. Information sharing between users may become increasingly important for blind travellers. GPS/satellite navigation systems already allow the sharing of points of interest and information sharing apps are being developed to allow information sharing about best routes and other features. If apps are designed to facilitate this, information sharing could be a way to overcome the lack of the very detailed information, such as the location of pedestrian crossings and bus stops required by blind people, in GIS and digital maps. Giving blind end-users control of the information available to them is clearly desirable. There are also arguments that this could reduce the onus on designers and developers to produce fully accessible systems. However, the discussion is beyond the scope of this chapter.

5.2 Interface Design

The system interface consists of input(s) and output(s). End-users use the input(s) to 'communicate' with the device, operate it and in some cases give it instructions. The output(s) are the means by which the device conveys information to the user.

In the case of simple mechanical devices such as the long cane to a large extent the handle serves the function of input, though the concept is less relevant than for more complex devices. For the cane it is again the handle which acts as the output and through which the user feels and can explore objects and the ground surface. However, good input and output design is likely to be more difficult in the case of more complex devices.

Since mobility devices are intended to be used while the user is moving the interface should be designed to be easy as possible to use while moving and preferably not require users to slow down or stop in order to use it. In addition both the input and output need to be accessible to blind people. The graphical user interfaces used in many mobile devices are both inaccessible to blind users and inappropriate to sighted users. In particular, they generally require too much of the user's attention and cannot be used in hands free mode, whereas the user needs to pay attention to avoiding danger, real world tasks and engaging with other people and needs their hands free for other activities [48], including for holding a cane in the case of blind people.

Accessible input includes speech, a keypad or keyboard a joystick or switch and press buttons. A multinational survey of blind people on attitudes to and preferences for different features of a robotic guide found that just over two thirds wanted speech input, just over two fifths a keypad and about a quarter a joystick or switch, with much smaller numbers interested in buttons [39]. Unfortunately, speech recognition rates in noisy environments are still low, leading to the possibility of error, and the voice recognition system generally needs to be trained. In addition, the ability of devices to distinguish between speech and non-speech sounds is frequently poor, leading to action easily being triggered by background sounds.

Speech input is most likely to be effective in mobility devices when used for a relatively small set of commands, with the expressions used very clearly distinct from each other. In addition, a means of indicating the start and end of each command, either through the use of a distinct sound or pressing a button on the device would be useful. In many, though not all, cases the restriction to a set of commands will not be a strong limitation. However, the need to indicate the start and end of each command could be irritating and will sometimes be forgotten. Another option could be to confirm command in response to a speech prompt. However, both these approaches could make speech input slightly less easy to use and therefore less attractive.

Other options suggested by survey respondents include the use of buttons and a USB or wireless connection for route planning, configuration and software updates [39]. Buttons are particularly suited to devices which only require a small number of controls. They should be appropriately located and tactilely distinct to make it easy for blind people to distinguish them from each other, including when the user is moving. Prototype 2D arrays of mini vibrators have been used to represent 3D information. Positioning them on the chest or back has the advantages of keeping the hands free, giving a direct relationship between 2D positions in space and on the display and allowing them to be hidden under clothes [9], thereby avoiding stigmatisation or other unwelcome attention. However, the back and chest are not particularly sensitive areas, so tactile displays using them may not provide sufficient resolution for complex spatial data. 3D virtual audio displays transforms audio signals into separate signals to the two ears that the user listens to through stereo headphones using different audio filters in the left and right ear paths. More complex version uses a constructed 3D scene model for each selected frame [48, 88, 89].

Multinational survey respondents have been found to have a very strong preference for speech output with only a small percentage interested in Braille [39]. Several respondents noted that Braille output would not be particularly useful due to the small percentage of blind people who know Braille and that the time involved in reading Braille would slow the user down. Braille output mobility devices, such as the BrailleNote GPS, generally also provide speech output. The BrailleNote GPS also provides a choice of Braille and qwerty key input. It can be worn with a shoulder strap, and could therefore possibly be used while walking slowly by guide dog users. However, safety considerations make it preferable for users to stop to use the Braille outputs and keyboard input.

Speech output has a number of advantages. In particular, it can convey both simple and relatively complex information in a format that most potential users find easy to understand. However, it can be difficult to understand or even incomprehensible in noisy environments. It will generally provide little comprehensible information to people with more than mild or possibly moderate hearing impairments, with understanding decreasing more rapidly than for people without hearing impairments with increasing noise. Other output options include musical sounds or other audio output, tactile indications and text messages. For instance, specific types of sounds could be used to indicate particular obstacles and vibration of the handle to signal approaching obstacles.

Other possibilities include a combination of speech and vibro-tactile signals, choice of synthetic voice, Braille and other options, a text message on a mobile phone or palmtop and different types of feedback to indicate different obstacle directions. Clock face information may be particularly suitable for given directions [65] and seems to be preferred by blind people. However, information can only be given in this format on one obstacle at a time. It is generally the object closest to the user within a certain arc in front of them that is most critical. Since the object position changes as the user moves, it may be more appropriate to use audio beepers [65] or other virtual sound located in the environment to indicate the direction. Where a device has more than one message to convey to users, e.g. about obstacle locations or safe path directions, the order of message delivery needs to be decided with information critical for the user's safety given priority over other information [65]. All audio information needs to be transmitted carefully to ensure that it does not block access to environmental sounds which are very important for blind people. This includes the consideration of the design of head phone or ear pieces used to convey the sound and the frequency and type of sound.

(Vibro-)tactile output has the advantage of being suitable for deafblind people, including those with significant hearing impairments. It can also be applied to different parts of the body, e.g. right or left wrist or shoulder to indicate the approximate direction of an obstacle or the direction in which the user should turn.

The distance to obstacles or other objects and obstacles/objects at different distances could be indicated by either different types of tactile input or sound, with for instance the frequency of vibration, repetition rate or loudness of the sound increasing as the object approaches. However, there is more scope to do this with sounds. In both cases users will generally require a relatively long period of training or familiarisation before they can easily understand the output.

The part of the body stimulated by (vibro-)tactile output is also important. The most sensitive parts of the body are the hands, lips and tongue. However, devices with vibro-tactile output to the lips and tongue are likely to be socially unacceptable and would interfere with speech. This would affect both the social interactions of blind people while travelling and their ability to ask for directions or assistance. Since this is an important component of independent travel for blind people [41] obstructing the tongue and/or lips would make travel more difficult for blind people. Suggestions of vibro-tactile output to the forehead via a hat [33] are also unsuitable. Stimulation of the head should be avoided due to the possibility of headache or even dizziness or disorientation and some users are likely to be concerned about the effect of the hat on their appearance. There are also issues of the appropriateness of hat wearing to the climate and its possible social and cultural implications.

Another tactile output option involves finger Braille with vibratory stimulation of three fingers on both hands [2]. This is less bulky and cheaper than other Braille displays and could leave the hands free for other activities, but does not overcome the problem of lack of Braille knowledge by most blind people. The robustness of the design would need to be improved, including through using stronger materials and either becoming totally wireless or wires being hidden. Another option involves using an existing mobile device, such as a mobile or smart phone, as the interface. This would have the advantages of familiarity, thereby possibly reducing the time involved in training, reducing costs and the use of a general purpose non-stigmatising device. In this case, a platform independent design would ensure the widest usage, though it should be noted that 82.8% of mobile devices had android operating systems in 2015 followed by iOS with 13.8% [51].

There are also still open questions as to what types of and how much information users can comprehend easily while travelling, the contextual and other factors that affect this, and how interface designcan facilitate information processing and reduce cognitive load. The answers to these questions are very important for device design. There will also be tradeoffs between the amount of information that can be relatively easily processed and whether the user is able to continue walking or needs to stop to use the device.

In summary, there is evidence that blind people have strong preferences for speech input and output, at least for more complex devices. However, the performance of speech input systems still needs improvement, speech output systems are unsuitable in noisy environments and for many deafblind people and need to be appropriately designed to avoid blocking access to environmental information. The above discussion also indicates that interfaces for blind people should meet the following conditions:

1. High quality
2. Low cost
3. Easy to use while the user is moving and preferably do not require users to slow down or stop in order to use it
4. Non-interference of any audio output with environmental sounds
5. A choice of (vibro-)tactile and audio output, with audio output options including speech, other than for simple mechanical devices.

5.3 Sensors

In simple terms mobile travel aids function by obtaining information from sensors, processing this information and transmitting it to the user through actuators of the user interface. Thus, sensors have a crucial role in mobility devices, with system performance dependent on the quality, quantity and type of information they provide. The types of sensors required and their prerequisite properties depend on the specific application. There may be tradeoffs between different desirable properties, such as low cost and high accuracy and precision.

Sensors which can be used in obstacle avoidance devicesto determine the position of objects include infrared, ultrasonic, laser range finders and (video) camera. Devices that use sonar can function in the dark, rain and snow, making them very versatile for outdoor operation. However, sonar echoes become distorted in crowded or confined places, making the information transmitted unreliable [30]. Laser range finders are generally more accurate than ultrasonic and infrared sensors, but they are expensive [39]. Camera-based devices work well in a range of indoor and outdoor conditions, but may have problems stabilising images when the user is moving and there can be considerable variation in illumination both within and between scenes [30]. More recent developments (e.g. [4, 63]) are able to provide additional environmental information through the use of cameras, particularly RGB-D, ranging or depth cameras with signal processing algorithms.

The most commonly used sensors in navigation and wayfinding systems are satellites, and infrared and RFID systems for satellite navigation systems and environmental information beacons respectively. As discussed in Sect. 3.2, there are significant differences in the types of information available in the two different approaches.

Inertial sensors comprising a combination of accelerometer, gyroscope and magnetometer, and optoelectronic sensors could be used in navigation and wayfinding systems to determine the user's orientation [61]. This is particularly important for blind people and can also be useful for sighted people, for instance when leaving a poorly signposted (large) unfamiliar railway station. Inertial sensors have the advantage of relatively small size and therefore being relatively inconspicuous and have been found to generally give satisfactory performance in terms of errors. Inertial and optoelectronic sensors have been found to give comparable results [61]. However, care needs to be taken when using sensors which include magnetometers to avoid interference from ferromagnetic materials. This may be a particular issue when the user is using additional assistive technology containing ferromagnetic materials which move independently relative to the magnetometer. Interference from ferromagnetic objects to which the sensors are connected, so that the motion is not independent, can be determined and its impact designed out. However, this is not possible when the motion is independent [61].

5.4 Privacy

As discussed in the previous section, most electronic travel aids use information from sensors. This potentially raises security and privacy issues related to protecting access to this information, determining who, if anyone, in addition to the user can access it and what information they are permitted to access. This may be dependent on the nature of the information, what inferences it allows to be made about the user and their attitude to privacy. Mobility aids that locate the user and/or obtain contextual information about them and/or the context of use raise particular issues, which should be, but are rarely considered in aid design. Some of the technologies involved such as RFID tags are particularly insecure and can be easily read by unauthorised people [81]. This could lead to the targeting of blind people who may be seen as vulnerable by ill-intentioned individuals, Security schemes for managing access to RFID information are being developed, e.g. [74], including for mobile RFID devices [73, 81]. However, in practice they are not generally used.

The lack of discussion in the literature of privacy issues associated with assistive technology implies this is rarely considered in assistive device design. Therefore, designers rarely provide information to end-users about privacy issues, making it highly unlikely that end-users are aware of them. It is quite probable both that different users will have different attitudes to privacy and that many blind end-users would be willing to accept a reduction in privacy for increased device functionality, particularly if this leads to increased independence. However, this should not be assumed and developers need to make information available to suppliers and end-users in clear language that can be easily understood by people without a technical background. They should also consult end-users about their privacy preferences and tradeoffs.

However, it is preferable to avoid users having to make choices between improved mobility (device functionality) and privacy. While, it may not be possible to totally eliminate privacy and security concerns, the use of privacy management and security systems can significantly reduce them and enable users to enjoy good device functionality with no or only a minimal reduction in privacy. They can be used to allow users to determine privacy settings and give them control over authorised access to information. They can also be used to significantly reduce the risk of unauthorised access, though it is very difficult to eliminate this entirely.

Privacy protection has been divided into eight requirements which need to be addressed in order to reduce the likelihood of the collection of data that can identify the user. Privacy protection approaches can be divided into the two categories of security requirements engineering which involves consideration of security and privacy issues in the early stages of system development and technological solutions in system implementation [55]. Security requirements engineering has the drawback of not linking the identified requirements to implementation solutions. Consequently, it does not take account of the important relationship between user needs and software capabilities. It is also possible that blind people may have privacy concerns relating to the functions they use the mobility device to carry out. This implies that protocols to ensure the anonymity of the user carrying out particular functions may be required or pseudoanonymity if full anonymity is not possible.

5.5 *Context Awareness*

Context awareness involves adapting or personalising information for the individual user [11]. Context is multidimensional. It includes physical, cognitive, temporal, social and application factors [11] and any information that is relevant to the interaction between the user and an application [1]. This allows devices to act in the absence of explicit user instructions in order to modify the system. The aim is to make interaction more natural and personalised and to reduce the need for end-user interaction, as this can often be inferred. This would have the advantage of freeing end-users to, for instance, concentrate on route learning, talking to a friend or enjoying the walk rather than interaction with the device. However, the extent and type of automatic interaction would need to be under end-user control to eliminate the possibility of the initiation of actions users disagreed with or the device controlling activities users want to retain under their own control.

An understanding of context can be used to identify the dimensions necessary to infer a user's activities and intentions and provide more relevant context-specific feedback. Contextual information can be obtained directly from sensors, through a middleware infrastructure which introduces a layered architecture with low level sensing or via a context server which gives multiple clients access to a remote data server [17]. Mobile devices generally have built in sensors and access data directly from them. However, they may also want access to remote data sources. Sensors can be used to obtain, for instance, data about the local environment and the user's state, and contextual resources, e.g. diaries to obtain information about the user's meetings and other activities. In addition, communications to external services, for instance via Bluetooth, internet protocols or messaging services can be used to obtain contextual information from them [80]. The different options for representing the context include the use of context widgets, as typified by the Contextual Toolbox [22, 86] the use of the blackboard metaphor [5, 95] and an infrastructure-centred distributed service model based on the client-server dialogue. The Contextual Toolkit provides a framework for using context widgets and other software components to represent the context and enable applications to access contextual information from their operating environment, combine it in various ways and increase its level of abstraction or otherwise process it. The blackboard metaphor uses a data centric approach. It is less efficient than a widget architecture, but more robust.

Context aware systems should also allow extension of data types to enable additional sensor-based and inferred contextual variables to be added to the system [80]. Contextual systems can also support and facilitate information sharing between users. Blind people already share verbal route descriptions and travel experiences [28] and points of interest on GPS systems. Context awareapps are able to do this in a much more sophisticated way, e.g. [20]. One of the problems in using data from unknown sources is its reliability. However, the volume of the data, even in the case of the considerably smaller blind than sighted population and the fact that correct data will be repeated, whereas erroneous data is likely to be erroneous in different ways, make it highly likely that the final result will be correct.

As discussed in Sect. 5.4 the collection, analysis and storage of user and contextual information raises privacy and security issues which need to be appropriately managed. Different users may be interested in different types of contextual information, want to use it in different ways and be able to process different amounts and types of information without this having a negative impact on travel safety. There is therefore a need for options for personalisation of the ways in which contextual information is collected, used and protected. User profiles could be used to store user preferences and dislikes in this area, as well as other aspects of device use, such as the preferred type of interface. Personalisation options also raise design issues of what, if any, design featuresshould be the default option and whether the selection of contextual features should be based on opting in or opting out or a combination of the two.

6 The Design Process and End-User Involvement

6.1 Stages of the Design Process

Design consists of a multi-stage iterative process with both frequent backtracking and overlap between the different stages. As already discussed, best practice requires user-centred design, which has been shown to lead to more usable systems and to save time in large projects [11]. This is particularly important for mobility (and other assistive) devices for blind (and other disabled) people as few designers of mobility (or other assistive) devices for blind people are themselves blind (or otherwise disabled). An example of the problems that can occur otherwise is illustrated by an article on future mobility technologies from the 1970s which suggested that the blind person of the future would be like a robot covered in technology and clanking and clicking as they walked. This shows a total lack of understanding of the social aspects of technology design and the fact that blind people are just as concerned about their appearance as sighted people. It also shows a lack of awareness of the importance of environmental sounds to blind people, since these sounds would presumably be drowned out by all the clanking and clicking. In particular this illustrates the problems that can result from designers using design approaches based on their stereotypes and misconceptions about the end-user group(s). Another common design error is design based on the characteristics, needs and preferences of the designer(s), even when they are very different from those of the end-users they are supposed to be designing for.

Most of the diverse approaches to user-centred design have the following four main steps [15, 32], which could be considered a model of user-centred design:

1. Learning about the users and their activities as early as possible, preferably right at the start.
2. Applying this knowledge about the users to inform the design.
3. Repeatedly presenting the users with early prototypes for evaluation.
4. An iterative cycle of design, (end-user) testing, measurement and redesign, which is repeated as often as necessary, to identify and take account of any issues identified in end-user testing and resolve the associated problems.

6.2 End-User Involvement

The design of effective mobility devices which are attractive to users requires an understanding of the target user groups and their goals, requirements, preferences [87], lifestyle, language, cultural and other contexts, which may be different from those of the dominant culture of the country or region they are in [72]. As indicated above, this is particularly important in the case of technologies for blind or other groups of disabled people. Only (potential) blind end-users fully understand their own requirements for mobility devices, can test what does and does not work in practice and determine whether the proposed device is useful to them and appropriate for their lifestyle. Appropriate functionality and good technical performance are clearly very important for mobility devices. However, as discussed in Sect. 4, a number of other issues including appearance and cost are equally important.

Decisions on functionality and mode of use are generally made early on, with changes at a later date likely to be both less effective and more expensive. Asking end-users about an existing design rather than consulting them and using the results to draw up a design could lead to a less than optimal result. There is also the risk of bias with designers being tempted to try to obtain information which supports their existing design [15] rather than investigating end-user opinions, requirements and desires. This further supports the importance of end-user involvement right from the start. The primary users of mobility devices are blind people. There are also secondary users, including orientation and mobility instructors, some family members and various other professionals. Their role in the use of these technologies is subordinate to that of blind end-users, who should be given the greatest consideration in the design process. However, there may be some value in consultation with O&M instructors, particularly with regard to any requirements for training to use the devices effectively and safely and information on how this training fits into the wider context of O&M training.

(Potential) funding organisations, including state/public healthcare and social services departments and a range of non-governmental organisations, are also stakeholders. Their interests and perspectives are not necessarily the same as those of blind end-users. Therefore, they should not be involved in the design process to ensure independence and the highest design standards [42]. However, designers of new mobility technologies should be aware that potential blind end-users of these technologies may require full or partial financial assistive in order to purchase them, though this should not lead to design compromises in an attempt to please potential funders. In addition, users are more likely to become aware of and therefore use devices that are available through social and/or health services, even if they have to pay all or part of the costs themselves. O&M instructors may also have a role in recommending particular devices to blind people, but are not involved in funding them. While, it can be useful for designers to develop relationships to inform instructors, social and health services and other potential suppliers and funders of available devices and their features, these relationships should not be allowed to influence the design process. It should also be noted that the availability of after sales information, support, maintenance and repairs is both useful to end-users and can positively affect decisions on supplying and promoting a device.

The involvement of end-users [42] can be broadly divided into the three categories of participation, consultation and research involvement. In participative approaches end-users generally represent one or more organisations, are members of research teams and participate in decision making and other activities in the research and development project. Their role is therefore analogous to that to other researchers and developers participating in the project, with a particular focus on their end-user expertise. In consultation end-users act as consultants and provide advice at different stages in the project, including initially, and are involved in testing and evaluating prototypes and finished devices. Research participants, who used to be referred to as research subjects, participate in questionnaires, interviews and focus groups, as well as experiments of different types, in addition to participating in similar activities to consultants. The basic differences are the treatment of consultants as experts and research participant as general members of the population of interest and generally asking for personal data from participants, but not consultants, for statistical correlation purposes and to check the whole population of interest is covered. Ethical approval is required for the involvement of research participants, but not of consultants.

Involvement of blind end-users in mobility (or other) device research and development requires consideration of the diversity of the population of blind people on factors including age, gender, race/ethnicity, education, employment, O&M training and skills, other impairments, extent of visual impairment and the age of onset of visual impairment. These and other factors may affect end-user requirements, preferences and the ways they use mobility devices. Doing this effectively may require consideration of cultural factors in the design of questionnaires and interviews and translation of information and questions into users' preferred languages. Care is required when translating questionnaires and interviews in cross and multicultural research to ensure that the meaning is not distorted and is equivalent in the different versions and cultural and national differences, including attitudes and institutions, are taken account of [43, 67]. This may include, for instance, differences in the school system with some countries providing secondary education in one school and others dividing it into upper and lower secondary schools. Even in this relatively simple case the use of inappropriate terminology could lead to misunderstandings, incorrect answers or even the withdrawal of potential participants.

Many blind and partially sighted people find printed documents inaccessible. Therefore, all documents should be made available in a range of different formats to take account of the accessibility requirements of the end-users' being consulted. This may include electronic formats which are compatible with screen readers and screen magnifiers, large print with the font size and colours suited to the particular end-users requirements and Braille, though only a minority of blind people are fluent Braille readers. It should be noted that PDF documents are not necessarily accessible [38].

Decisions on different design factors may involve the presentation of mock-ups of the device to end-users. The mock-ups need to be designed in a way that enables their main features to be investigated by blind people. Some care will be required with this, since drawings or cardboard cut-outs which are investigated visually are generally not appropriate. Further issues related to end-user involvement and some of the approaches are discussed in Hersh [42].

6.3 Device Testing

There are numerous reports in the literature of device testing by blindfolded sighted people, presumably because the researchers have found it easier to find sighted than blind volunteers. While this may be acceptable for the earliest testing stages, the travel strategies and spatial knowledge and understanding of blindfolded sighted and blind people are not identical. In addition, factors such as age, age of onset and history of visual impairment, experience of early exploration and experience of O&M training and the presence of additional impairments, will affect blind people's travel experiences and performance. Therefore testing needs to involve blind people with a variety of personal characteristics to obtain a real understanding of device performance, acceptability and attractiveness to potential end-users. There may be value in combining end-user field tests with usability measurement studies by measurement professionals [71], with particular benefits from the involvement of blind and partially sighted professionals. However this may require more blind and partially sighted measurement professionals to be trained.

Device evaluation often involves measurement of the time required to complete tasks, but this is insufficient on its own. In addition, confidence in the device, the provision of accurate information, successful task completion, ease of use and safety may all be very important to potential end-users. Therefore, full evaluation will generally require consideration of a number of different factors and should usually include both quantitative data on user performance with the device and qualitative data on user subjective opinions of it. It is also useful to record and analyse different types of errors to determine which ones were device related and which a result of, for instance, misunderstanding the instructions. It is also important to obtain users' opinions of the device and subjective impressions of task difficulty both before and after the experiment [66]. Various factors related to how performance evaluation is carried will affect the results. For instance, the length of time allowed and whether and when participants are allowed to ask for assistance can also affect performance.

The amount of training in device use before tests are carried out will frequently affect both performance and user safety. There are also issues of the duration and type of training and experience using the device required for meaningful results can be obtained, particularly in the case of more complex devices. There are clearly advantages in the development of devices whose use is intuitively obvious and at most requires a simple list of instructions. However, the complex information provided by some electronic cane (extension) devices requires an extensive period of familiarisation before participants can use the device safely and effectively and obtain maximum benefit from it. This then raises the question of the point in the training/familiarisation cycle at which testing should be carried out so as to obtain appropriate trade-offs between participants' time commitment to a device that may not be developed and the likelihood of obtaining useful results. It may also be useful to obtain estimates of the average length of trainingrequired to obtain particular levels of performance.

Quantitative measurements commonly used for obstacle avoidance devices include the number of contacts with obstacles and the percentage of preferred walking speed (PPWS) with the device, which has largely replaced measurement of time or speed [76]. Preferred walking speed can be obtained by measurement of walking speed on a straight course without obstacles when the person is using their standard mobility aid or walking with a sighted guide. PPWS is obtained by measuring walking speed when using the device in different circumstances and calculating the ratio of this to preferred walking speed. It has the advantage of allowing participants to act as their own controls and giving an automatic comparison of performance with and without the device (Patel et al. 76). However, in some cases the use of mobility devices will lead to a reduction in PPWS due to the time and cognitive effort associated with device use, but will have other benefits such as enabling users to travel more widely on their own. In addition, PPWS with the device may increase with training and device use. In the case of wayfinding devices other useful measures could include the number of times the user has to backtrack and the ratio of the length of the route followed compared to the minimum length route that meets the user specifications.

Safety is a very important issue when blind people test mobility devices. Initial end-user testing of prototypes and devices can take place on constructed courses with carefully placed obstacles and no moving traffic, but end-user testing in real environments will also be required to fully understand the features and performance of the device and user reactions to it. Even unfamiliar constructed courses have some risk, due to the presence of obstacles and the use of a new device with which the user is not yet fully familiar. Therefore, safety monitoring is essential at least in the initial and intermediate stages of device testing until the safety of the particular user with the device has been established through extensive testing. This should preferably be carried out by an O&M instructor and otherwise by a person with appropriate expertise and experience and/or training. In most cases the safety monitor should only monitor one blind person at a time and not concurrently be involved in observation or other aspects of the research. They should remain alert and be ready to intervene swiftly to remove the blind person from potential harm if necessary. The safety of participants should be of paramount importance at all times and override any other considerations. It is therefore prudent to design end-user tests in such a way that they can be easily restarted after any necessary interventions to remove participants from potential danger.

7 Conclusions

Design is an complex and multi-dimensional topic. Therefore, even in a relatively long chapter it is not possible to give more than an overview. The chapter has stressed the importance of the involvement of blind, partially sighted and deafblind end-users from the start and throughout the research, development and design process. An understanding of how blind people travel, including the ways they use information from all their senses and travel aids, is a further essential prerequisite for good design. While an overview has been provided, indepth understanding can best be obtained by interaction with blind people.

The chapter has also provided a brief presentation of the different phases in the development of travel aids, a summary of the different ways of categorising them and some principles of good practice for developing new travel aids. Specific features, such as the sensors, interface, privacy management and contextual features, have also been considered.

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Co-designing together with Persons with Visual Impairments

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1 Introduction

The importance of involving the persons intended to use a design, already in the design process leading up to the final product or service, is increasingly acknowledged. This chapter is intended to provide both inspiration and practical suggestions for anyone interested in designing for and with persons with visual impairments. The text focuses on co-design, but many of the adaptations and materials presented can also be used in more traditional design activities, such as usability testing. The chapter rests on an inclusive mindset. In other words, we focus on how to expand and enhance existing methods regarding who is involved, and how to provide means for participation to wider target groups, rather than how to create “special” methods for “special” users with “special” needs.

The chapter starts with a general background on the design process. This background is followed by a discussion of human-centred design and co-design, and why the visual ability of the persons involved in the process matters. We then present six concrete examples of design activities from our own work. These examples have been selected to be inherently different, and are intended to serve both as illustrations of how useful it can be to engage in co-design, and as practical inspiration for future design activities. We hope to show that there is no need to feel daunted by organizing design activities together with persons with visual impairments—in fact there is a wide range of possible activities you can engage in together with your future users. The examples are followed by a discussion of activities and materials, inclusive design and accessibility and the importance of the context of use. The chapter ends with a conclusion/take away message.

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2 The Design Process

A typical feature of any design process is that much information about "the problem" (the persons involved, the way things are used, the surrounding context, etc.) is missing at the start of the process. And since the way the persons involved behave, the way tasks are handled and the context typically changes as artefacts change and new artefacts are introduced, the design process aims at a moving target. To get to the goal the design work needs to start before all relevant knowledge is available—the design process itself will be a tool for gathering the necessary knowledge. In the words of Donald Schön [33–35] one needs to start a reflective conversation with the materials:

> There is no direct path between the designer's intention and the outcome. As you work a problem, you are continually in the process of developing a path into it, forming new appreciations and understandings as you make new moves. [34]

In a sense this can be termed "doing for the sake of knowing". Actions are not just actions to produce a certain result, but rather acts to inquire into the current design problem. This type of actions can be used to explore or to experiment—to physically test your ideas in the world [9]. An important point in Gedenryd's thesis is that design is not a purely intramental activity—instead the interaction with materials (in a broad sense) forms an integral part of the cognitive process.

The designer and the design team is progressively moving along, making judgements about different responses from the medium—and sometimes discovering completely unexpected things. Schön uses the term *backtalk* for this type of surprising discoveries—the materials talk back at you telling you things you did not know [34].

Donald Schön introduces the concepts "reflection in action" and "reflection on action" in his classic book *The Reflective Practitioner* [33]. *Reflection in action* is different from just knowing how to act, how to do. Reflection in action is closely linked to an element of surprise. A person responds to an unexpected outcome (good or bad) by thinking about what he or she is doing, in a way that influences further doing. Examples given are a group of jazz musicians who note and respond to surprises introduced by other players, or a designer conducting a set of experiments through drawing a series of sketches and responding for example to unexpected constraints posed by the environment.

In some situations, the person instead responds to the surprise by stopping to think about what happened. In this case it is a matter of *reflection on action*. A member of the design team may pause to think back over what has been done in a project and exploring the understandings that were brought into the process and framing new theories [34]. Of course one may also reflect on practice. This is a higher level type of reflection which involves patterns of behaviour.

If the final product is to be usable, then the persons who are expected to use it, as well as the usage have to be part of the described processes of reflection and action.

Furthermore, the cost of implementing changes becomes larger, the closer to the finished product we are getting in the design process. Thus, we would like to involve the right persons and contexts in the process right from the very start.

3 Human-Centred Design

In the traditional waterfall model for engineering design [31], the basic idea is that you first find the requirements for the future system, then you design and build it, and finally you evaluate it to see that it fulfils the initially specified requirements.

Unfortunately, user requirements are typically hard to find out. There is usually much more to understanding what is wanted, needed and desired, than to ask people what they want. Confronted with the question "what do you want," most people will actually answer with a question of their own: "what can I get?". It is also very difficult to know surely exactly what one wants in a specific situation without being able to try it out. In addition, the situation of use will be changed in the presence of new artefacts. Thus the persons who will be the future users of the product or service, as well as the context of use, need to be continuously involved. It is against this background the user centred or human-centred design has been developed. Human-centred design acknowledges that design is iterative, and that the requirements need to be updated as the design process progresses towards a final product.

Human-centred design is currently well established. There is even an ISO standard (ISO 9241-210:2010 Human-centred design for interactive systems). The terms user centred and human-centred are often used interchangeably, but since "user" limits the role of a person to that of a user we suggest "human" is more appropriate—most persons are much more than just a "user". Technology use is normally only a part of an activity and we cannot generally expect that the goal of the activity is to use technology. We should be designing for people, not just for users. Despite this we will (for brevity) in the following continue to use the term "user" when referring to the person who is expected to make use of some current or future technology.

As defined in ISO 9241-210, Human-centred design is a process where the components "understand and specify the context of use", "specify the user requirements", "produce design solutions to meet user requirements" and "evaluate the designs against the requirements" are iterated until there is a good solution that passes the evaluation. Two key concepts are also defined:

Usability: the extent to which a system, product or service can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use.

User experience: a person's perceptions and responses resulting from the use and/or anticipated use of a product, system or service.

There are many ways to involve users and their needs, wishes and dreams in a design process [29]. The approaches and techniques for user involvement are so numerous that [17] explicitly states that user involvement is a vague concept. In some approaches users take active roles in different design activities, while in others they are providers of information, commentators or objects for observations. Users can also be involved directly in person, or indirectly through guidelines, checklists, personas, scenarios, simulations or other tools/techniques that capture indirect information about the user and the context of use. Thus, user involvement can be both direct and indirect, while the level of user involvement can vary from informative, through consultative to participative.

As is stated above, the importance of involving users in the design process is well established. And not only users—the context of use is just as important. According already to Lueg and Pfeifer [19] human cognition should be considered to be emergent from the interaction of the human with the environment, i.e. the current situation the human is involved in. Thus, to obtain working designs one needs not only to involve users in the design process, but also involve real usage situations as much as possible. Laboratory tests may provide information about how a user can use a device or a system, but one can never be sure about how valid this information is for real contexts of use.

4 Participatory Design and Co-Design

Participatory design and co-design is a subset of human-centred design where the design is done *with* the users, rather than *for* the users. The *mindset* in co-design/participatory design is that users are not just sources of information—they are active participants in the design process, contributing knowledge and perspectives that would not be reached otherwise. This mindset is crucial, since it will influence not only the way you think of your users, but also the way the whole design process is carried out: the way you design different design activities and how you work together with the users. The overall mindset of co-design is thus a necessary component for this type of design projects.

An often cited early participatory design project was UTOPIA [5] which in the early 80s set out to design a graphic workstation for a newspaper together with the newspaper graphic workers. In this project the graphic workers were seen as co-designers, and mutual learning between the researchers and the workers was an explicit activity in the project. The participatory design toolbox has been extended since UTOPIA, but central to this approach is low technology prototyping and design sessions or workshops together with the intended users of the future technology. While participatory design has strong political roots, and was originally developed for design within a workplace environment, co-design can be used as a more general term for design activities involving future users as co-designers [32].

A common type of design activity in co-design is the design workshop. Workshops are hands-on sessions where small groups of persons (end users, professionals, etc.) work creatively together. The key is the group work, allowing for a creative interaction between group members that involves elements of brainstorming (expressed ideas lead to new ideas). At a workshop one can work with concepts, technologies and practical examples. Normally a workshop consists of activities ranging from discussion and idea generation to creation and implementation of simple prototypes [24].

It should be noted that co-design is not the same as design done by the users. The observations "Users are not Designers", as well as the counterpart "Designers are not Users" [28], are still relevant. What we strive for is for the users to be active and creative contributors in the design process *together* with the specialists in the design team. Contributions may take the form of actual designs or creative input for design. Co-design activities typically also provide an improved understanding of the current design "problem".

5 Co-designing Together with Persons with Visual Impairments

Looking at existing methods for co-design and participatory design, it is obvious that there is nothing that per se makes these less suited for use with persons with visual impairments. The difficulty lies in the fact that many standard design tools like Post-it notes, drawings, cards, videos and lo-fi paper prototypes are visual tools. Thus, anyone working together with persons with visual impairments typically needs to put in extra work in creating or adapting activities in order to make them suitable for non-visual use. In many cases adaptation can be straight forward like using tactile prototyping materials instead of pen and paper or using NFC or RFID tags to sonify objects. Sometimes the translation may seem simple but can turn out to require more work than initially expected—an example is lists of words relating to experience, e.g. happy, sad, interesting, boring. Such lists often contain words like light, bright or dark that refer to visual impressions, and a proper adaptation should include making sure words relating also to sound and touch experiences are included.

To make co-design practices more concrete, in the following we present six practical examples of co-design activities that have been used together with persons with visual impairments. These examples are taken from our own work. The examples have been selected to show a wide range of activities and materials. The first example is a single lo-fi design activity using LEGO bricks, the second example is a more elaborate study involving focus groups, a diary and a hands-on prototyping workshop. The third study is a more implicit design activity where participants design their system by asking questions to a person impersonating a mobile navigation system. The fourth example is again a combined study aimed at understanding sound and touch preferences among visually impaired children. This example is longer, and is divided into the subsections questionnaires, sound and touch workshops and sound story workshop. The fifth and sixth examples are a game creation game creation workshop and a gesture creation workshop carried out together with visually impaired children.

Example 1: VR Prototyping Using Functional Prototypes and LEGO Bricks

This example comes from a master thesis project at our department [37] aimed at exploring different ways to navigate a haptic VR environment non-visually through touch and sound. Virtual Reality (VR) is usually visual. By using interactive haptics like the Geomagic Touch (formerly the PHANToM), it becomes possible to make VR environments that can be used also through touch.

It is, however, generally difficult for end users to contribute ideas to the development if they have no experience of the technology to be used. While sighted persons have usually seen VR (or at least images or videos of it), and thus have a general idea of what it is and how it works, the situation can be quite different for a blind person. When dealing with novel technology unfamiliar to the user, one generally has to show working examples in order to provide the persons with an idea of what the technology is and how it works. At the same time such examples risk influencing/guiding the users and cannot generally be used as the sole basis for the open-ended mindset needed for innovative designs. In this example, the solution used for this dilemma was to combine working examples of VR environments with lo-fi exploration using LEGO bricks, in order to have lo-fi designs that could be accessed through touch.

At a workshop together with persons with severe visual impairments, participants were first allowed to explore some existing PHANToM environments. After this a simple room environment built using LEGO was presented, and a LEGO doll with a cane representing the avatar (Fig. 1) could be manipulated in order to explore different navigation alternatives. This way, the workshop participants could discuss how it should be possible to affect the avatar in the game world to accomplish movement, change of direction and interaction with objects.

Through the LEGO model (with the initial technology exploration as a basis), the participants were able to provide suggestions that could be incorporated in the first functional prototype.

Fig. 1 Lo-fi VR environment with an avatar using a cane

Example 2: Hands-on Design Workshop

This example comes from the HaptiMap EU project (www.haptimap.org), and was published in [23]. The study was part of the early work in the project which was aimed at eliciting user requirements from different user groups for navigation and map software. The study consisted of three parts: a focus group/test, a diary study and a design workshop where the users envisioned new kinds of interaction with mobile navigation systems by building and demonstrating low-fi prototypes.

The initial focus group consisted of two parts—one where the participants sat in a conference room and discussed navigation (strategies, problems, etc.), and one where the participants discussed while on the move, testing an existing navigation system. The difference in the discussion between the indoor stationary setting and the outdoor mobile context was considerable—indoors the discussion revolved around more general and high level observations on navigation while the outdoor mobile context triggered details and comments in a way the indoor stationary context did not.

After the initial focus groups, the participants were asked to keep a simple diary answering a few predetermined questions each day during one week (visually impaired participants got the diary electronically). Although the diaries provided some information, their most important function turned out to be *priming*: to get the participants to start thinking actively about navigation before the design workshop.

Since the purpose of the workshop was to create a mobile navigation system, the props were selected and also pre-designed to simulate common devices. The participants had access to models of mobile devices glued together from rubber material, as well as suitable materials for mimicking earphones, wristbands, cables, etc. (Fig. 2). When the groups had constructed their prototypes, they presented them to the researchers and then conducted a "simulation walk" with the device. The simulation walk was made indoors, but the users were instructed to envision outdoor use. The simulation walk was made to demonstrate the functionalities of the prototype device in a live setting.

The sequence design used was found to work well. The inclusion of existing technology in the focus group discussions provided technological reference [15] for the users, while the scenario walk provided the necessary context (during the walk comments were made that were not triggered in the preceding discussion). The

Fig. 2 Lo-fi mobile devices and materials

diaries provided some information and also prepared the users for the final workshop, although it was suggested by some users that the diary should have been kept over longer time. The workshop finally, showed that also for non-visual interaction design, lo-fi workshops can be a useful tool for involving users in the design process. The workshop and discussion turned out to be a fruitful arena to get into detailed questions about the functionality of the system.

During the simulated walk, both users and researchers were in the context of a way-finding task, however artificial, which triggered questions and also made more plausible that both parties were talking about the same thing.

A caveat based on observations at other similar workshops, is that it matters how lo-fi workshops are presented to the participants. Unless the activity is framed properly, it may be considered “childish” or a “kindergarten” kind of activity. Another caveat is that moderation may be needed if some persons in a group becomes too dominant (just like in a focus group). Thus, it is recommended that several persons from the design team are present.

Example 3: The Mobile Oracle

The Wizard of Oz (WOZ) type of prototyping, where a human fakes the functionality of the—not yet developed—technology, makes it easy to test auditory interface prototypes and can thus be useful when developing technology aimed at persons with visual impairments. In the “Mobile Oracle” [20] WOZ is combined with the information on demand technique [30] (Fig. 3).

The user was instructed to request information from a person impersonating a mobile service. The person was instructed to ask for the information when he/she

Fig. 3 Pictures from the test environment (a mall)

felt it was needed in order to perform a navigational test task. To further strengthen the idea of asking for information, the person impersonating the service was called an "oracle", since oracles are persons who you come to with questions. The test was carried out in November, and was set inside a shopping mall. The test task was to shop three specified items in different stores.

While using a mall for the test was useful since it made it possible to run the test even if the weather outside was bad, a mall as a testing environment has its own sets of problems. Firstly, there were restrictions on how the test could be documented—video filming was not allowed and we were not allowed to take photos of the ceiling. Sound recordings were fortunately allowed. At the pilot test an observer shadowed the test pair (the oracle and the test participant) taking notes, but this attracted too much attention and the note-taking was left out during the real test. During the real test a mobile phone held by the "oracle" recorded the dialogue. As a precaution we visited all shops beforehand to explain to them what it was we were doing.

The main outcome of this study was the questions asked by the test participants. These turned out to be very informative and provided rich input for the design process. The questions were also grouped, and the resulting overall categories "Content overview", "Spatial layout", "Direction/route", "Distance", "Notification/prompts", "Confirmation", "Content", "Recommendation", "Memory", "Time" and "Capability of the device" agree in general with what was found in earlier studies on navigation confirming the validity of the "Mobile Oracle" approach.

Both persons with visual impairments and sighted persons participated in the test. Many of the questions asked were quite similar, but there was a clear tendency for participants with visual impairments to ask for more details (e.g. distances in metres).

Example 4: Sound and Touch Preferences

This study [21] was done within the framework of the ABBI project. This project is aimed at developing a wearable device (a bracelet) intended to support sensory motor rehabilitation of children with visual impairments. The selected example is an exploratory study of aesthetic/hedonistic preferences for sounds and touch experiences among visually impaired children. Mixed methods were used: questionnaires, workshops (Fig. 4) and field trial using a mobile location based app for story creation.

The reason for the mix was that preferences may vary depending on context (e.g. a scary sound may be acceptable in a movie, but disliked when you hear it in real life). This led us to use methods combining questionnaires and rating of sounds ("is this sound pleasant or unpleasant") with more creative activities involving creating interesting "toys" and location-based sound stories. The rating of sounds and the creation of interesting "toys" were performed at three workshops at the Chiossone Institute in Italy (one workshop with habilitation personnel and two workshops with children with visual impairments). The creation of location-based sound stories took place at an invited activity at a summer camp for visually impaired children in Sweden.

Fig. 4 Sound and touch workshop design exercise

This method mix included both activities intended to capture direct preferences —your immediate reaction in terms of pleasure/dislike upon hearing a sound—but also more activity related preferences: how do you react to sounds and tactile experiences when these are assigned to a toy, and what kind of sounds would you like when playing and telling stories?

In the following we describe the different methods in more detail.

5.1 Questionnaires

To get initial information on sound preferences—but also to get the children to start thinking about their sound preferences—a short questionnaire was distributed and digitally and answered before the three workshops in Italy. The questionnaire contained the following questions:

- Please describe shortly a sound you think is pleasant to listen to—and if possible add a comment on why you like it.

- Please describe shortly a sound you think is unpleasant to listen to—and if possible add a comment on why you don't like it.
- Please describe shortly a material you think feels pleasant to touch—and if possible add a comment on why you like it.
- Please describe shortly a material you think feels unpleasant to touch—and if possible add a comment on why you don't like it.

5.2 Sound and Touch Workshops

At the workshops we explored what kind of sounds and materials the children thought were pleasant or unpleasant. The workshops were designed with two exercises:

1. Exercise 1: a focus group type exercise where 71 different sounds (32 natural and 39 synthetic) were played and the children could raise their hands if they liked/didn't like them (or do nothing if they felt neutral). Hand raising was selected since it allowed the children to answer simultaneously without influencing each other too much (since the children had visual impairments, their ability to see what the others were doing was limited).
2. Exercise 2: a design exercise where the children were asked to combine a tactile object and a sound to make a nice, cool or interesting "toy". Children could associate one of the 20 sounds stored in an NFC tag and play it back by touching the material with a smart phone, or by vocalizing their own sounds.

After a pilot workshop it was decided to change the order of the sounds in exercise 1 so that the natural (potentially more interesting) sounds were played first.

5.3 Sound Story Workshop

At this workshop we used a location-based app to allow visually impaired persons to create and experience outdoor story trails. We had been invited by the persons arranging a summer camp for children with visual impairments to arrange a fun location-based activity, and decided this could also be a good opportunity to gather more information about sound preferences in a more realistic situation. In order to do so, the natural sounds from the sound and touch workshops were added to the app, so that for each story GPS point location one pre-recorded natural sound could be assigned/played alone or together with a voice recording. A few synthetic sounds were also added: a long square and sine tones, a low synth, white noise, piano and high and low ping sounds. The selection focused on timbre, and included both clean/bright sounds and muffled/noisy ones. The app was an android app, and had only a single trail.

The activity was designed as group work in a series of one hour slots where 8 children divided into 3–4 groups of 2–3 persons would first get a joint short introduction and try an example trail. The groups in the first time slot tried an example created by the researcher while following groups tried a part of one of the trails created by the groups in the previous time slot. After this they created their own trail, tested it, and if there was time swapped phones with another group and tried theirs. The researcher together with persons working at the camp were available as support in case of technical problems.

Due to the nature of the activity (a summer camp) the activity could not be tightly controlled and we were unable to film/record or gather personal data. The only material saved was the created trails, which were copied and stored after each slot.

The results from these activities showed that preferences vary, indicating a need for flexibility and personalization. Even so, sine or square tones were less liked, while sounds with more harmonics (wider frequency content) were in general better appreciated. Moreover, long continuous sounds were in general considered more unpleasant than short or repetitive sounds. Birds and water sounds were generally popular, while sharp, sudden and loud sounds were disliked—but the creative exercise and the story telling showed that also the unpleasant or drastic has a role to play. The sound story creation exercise furthermore allowed us to identify several roles for the sounds in storytelling and potentially during play, that needs to be considered: facilitate creation, sound effects, story elements, ambience and inspiration.

For tactile materials, soft, furry and hard materials were appreciated, while sharp, rough, hard, sticky, rubbery and runny materials were less well liked. Thus, materials common in toys and play materials like finger paint, play dough, balloons and rubber toys may not always be appreciated by children with visual impairments.

The methods used generally worked quite well. The few questions in the questionnaire generated a lot of useful results, as did the sound story exercise and the creative workshops. The tangible representation of the sounds allowed participants to physically manipulate and select different sounds (although moderator support was provided to keep the apps on the phones working). With tangible objects it was possible to sort sounds in piles and also to revisit and refine selections. Additionally, having tangible sound objects allowed the children to physically associate a sound with a material—a design which appeared well suited to the participating children. The activity that yielded the least interesting results was the hand raising exercise. It took quite a long time to go through all the sounds, and given that the overall result was basically “preferences differ” and that we got the essentially same information from the initial questionnaires, it is questionable if this was time well spent.

Example 5: Game design workshop

This workshop, which just as the previous example, was performed as part of the ABBI EU project [25] illustrates an activity which served both as a test of the technology and as input for how to use the technology. Before this workshop was organized, the ABBI sound bracelet had been tested in ad hoc individual rehabilitation, but since this type of device also holds potential for more social and playful activities we wanted to explore how the ABBI bracelet could be used in social games and play. Three workshops were organized: two together with a group of children with visual impairments at the Chiossone Institute in Italy and one together with children with visually impaired children together with their sighted siblings and families in Sweden.

The workshops in Italy started with an exercise where all participants had an ABBI bracelet. As a first “priming” exercise the bracelets were assigned sounds in pairs, and the task was to find the person who had a bracelet making the same sound as your own bracelet. After this the children were divided into groups and asked to design games of their own using the ABBIs (Fig. 5).

At the workshop in Sweden the initial task also included playing the game “statues”, created by one of the groups in Italy, where the goal was to walk as far as you could without the ABBI making a sound. After this introduction, children and family members were again divided into groups and asked to design games that involved the ABBI bracelet. All workshops ended with the different groups demonstrating their games.

The workshops resulted in a range of games which have later been used in the rehabilitation training, and clearly showed how useful it is to involve children in creative exercises—several new types of games were created that the design team had not previously considered. This exemplifies that co-creation activities work well not only with sighted children [4], but also with visually impaired children. At the same time the activity provided an important usability test of the technology, and key usability problems were identified: LED lights on the device were working in a non-standard way, a mute button and a simpler way to change the sound of the device was needed. Important points to consider when organizing this kind of activity with prototype technology:

- Make sure there is a backup if the technology fails. In our case we had made an app that allowed a phone to work as a replacement ABBI.

Fig. 5 ABBI bracelet together with a mobile device used to control the device settings. By default the ABBI is quiet when it is stationary, and only makes sounds when it is moved

- Think about how you present tasks to allow everyone to access the information, but also about how participants can share what they do while working together or when demonstrating their work.

The selection of sounds again confirmed the results from the initial studies [21], which showed the importance not only on nice and pleasurable sounds, but also of unpleasant or drastic ones. Running around "exploding" at every step, sounding like an elephant, like a mosquito or making rhythmical musical sounds is quite a different experience compared to walking around making a "ping" at each step. At the same time, we saw that it may occasionally get noisy, and in the post activity interviews at Furuboda a common suggestion was to provide a mute button (input for the usability evaluation).

Moving on to the game creation, as expected we saw that many of the created games were of a "find the sound" type. Complementing this was the "avoid the sound". Both these appear in the game "hide and seek": the chaser tries to find the sound source, whilst the person being chased tries to avoid the sound of the chaser (this game was designed and played by the two blind participants in Fig. 6). An interesting use of the ABBI was to rely on the fact that it was silent when it wasn't moved. This way one can create "sneaking" games, where the goal is to avoid being noticed. These kind of games had not been discussed in the ABBI design team prior to the workshop, and it can be noted that "non-activation" does not feature in the identified related work [1, 2, 16, 38].

Example 6: Gesture Design Workshop

This final example also comes from the ABBI EU project. Since the ABBI device is the size of a matchbox and lacks a screen, a smartphone app is used to control the device. The app allows the user to change volume, sound parameters, etc. The device has an accelerometer which is used to control when sound is played (to save battery the ABBI is silent when it isn't moved). A shaking gesture is used to wake the device up when it has entered sleep mode, but apart from this gestures are currently not used to interact with the ABBI. It has been suggested that gestures

Fig. 6 *Left* Initial finding exercise. Blindfolds were used to put everyone on an equal footing. *Right* Two blind children, probably for the first time in their lives, playing tag/hide and seek

designed by end users are easier to remember [27], and thus we decided to organize gesture design workshops together with our visually impaired end users at the Chiossone institute in Italy. Two workshops were organized, one with blind children (5 girls aged 12, 12, 14, 15, 17) and one with children who had low vision (3 boys aged 8, 11, 15 and 3 girls aged 10, 13, 15).

At the workshop the participants had access to ABBI devices. One of these was a new version of the ABBI which also had a small button. This ABBI was sent around the table so that all the children could feel it. The children were told that would like their suggestions for gestures for the different functions we would be presenting. Additionally, we explained that a "gesture" could be anything from pressing the button on the device, shaking the device, tapping on the device, waving it about or manipulating it in some other way. We then explained the functions one by one and asked the participants for ideas for each presented function. The functions investigated were mute/unmute, change the volume, change the sound, change the sensitivity and change between pre-programmed settings. The new ABBI firmware allows four different sets to be saved, and we wanted to investigate how one could interact with this functionality. The workshops were video recorded, transcribed and translated to English.

The children at both workshops came up with several suggestions for the mute/unmute, change volume and sound functions. The sensitivity—how quickly the ABBI responds to movement—and the saved settings turned out to be more abstract and the children found these more difficult.

In general, the children preferred making gestures *on* the device to making gestures *with* the device. Gestures shown on the device were mainly tapping and sliding. This was a conscious decision in the first group where one child commented that bigger gestures could cause accidental activation: *if the movement is too big it will be difficult to be used in everyday life as it could make it sound when we don't want it* and that control gestures are different from the movements you make during rehabilitation: *but then it should be a movement that we don't do all the time*. In the second group there was no discussion about this—in fact the discussion turned almost immediately to hardware buttons/wheels. Still, also this group suggested tapping and sliding gestures for sound changes and there was even one tentative suggestion put forward that shaking could be used, although the discussion immediately moved on from there and the suggestion wasn't elaborated on.

There is a clear difference between the groups, where the first group provide more gesture ideas while the second group quickly zooms in on adding additional hardware. Our interpretation is that this has less to do with the visual ability of the children involved, and more is due to age and mobile phone experience (some of the younger children did not use a smartphone). In fact one of the children explicitly refer to the smartphone when discussing rotational gestures: "*we could use the rotatory movement as in the smartphone*".

An observation made during the test was that while it was quite easy to discuss and demonstrate gestures, it turned out to be quite hard to share them with the whole group. When needed the test leader would demonstrate a gesture to all children in the group, showing it to one child at a time. The original workshop design had involved the children working in pairs where this would have been less of an issue, but it was decided for practical reasons at the last minute to have the workshop more as a joint brain storm/focus group. The children were still quite good at explaining what they meant, but it is possible that this also skewed the discussion in favour of gestures that were easy to explain. Given that the gestures implemented should be both easy to explain as well as easy to remember, this is not necessarily something negative—but it is a bias one needs to be aware of.

This workshop provided the design team with useful design suggestions, and is an example of the involvement of end users also in more concrete design work later in the design process.

6 The Overall Challenge Lies in the Activities and Materials

The above examples were selected to range over a variety of different activity designs and contexts. All involve some element of creative work—in the mobile oracle study the participants implicitly designed their navigation system through the questions they asked, while the other examples involve explicit design activities. While it is easy to find papers on co-design with children [3, 11, 14, 40] and adults [32, 41]—the cited works are but few of all the studies that exist, and there is even a journal devoted to co-design/co-creation: CoDesign: International Journal of CoCreation in Design and the Arts—co-design work that involves persons with visual impairments are fewer. In addition to the above mentioned work, another example is [26] where the authors worked together with children with visual impairments to design games. The work involved hands-on prototyping of toys as well as monsters and for the lo-fi prototyping clay, fixed design elements (e.g. buttons and dials) and different fabrics/fillings were used.

The examples in this text provide ample illustration of the fact that there is nothing per se, that prevents the involvement of persons with visual impairments in co-creative design activities. That having been said, there are some practicalities which anyone working together with persons from this group need to consider:

- Consider how you can support the sharing of information between participants during the exercise.
- Also consider how information before, during and after the activity is made accessible to the participants.
- When asking people to be creative it often helps if they can think about the “problem” beforehand. This is true for all users, but when dealing with persons with visual impairments you need to make sure also the priming information or activity is accessible.
- Provide multiple means for people to engage with and participate in the design activities, for instance by working with several modalities.

- Make sure you have a plan B for failing technology. Again you need to think the plan through so that it works for your intended users.
- A specific consideration if you organize activities at your lab is the question of transportation. As a sighted person it can sometimes be hard to describe how to get to different places in a way that suits a person who has a visual impairment.
- If you need people to sign papers, think about how this is done. It is always recommended to send information beforehand to participants, but this becomes even more important if participants are not able to read printed text. By sending information electronically beforehand the person will be able to access it using a screen reader. If your participants can read Braille (this is not always the case) it can be a good idea to also have some braille printed information.

As we see from this list, the design of the activity, and the materials need special consideration. For lo-fi prototyping different types of tangible materials (LEGO, rubber, cardboard, pipe cleaners, clay, fabric, string, etc.) can be used. Having a human faking functionality (Wizard of Oz) is often well suited also for non-visual interaction. Depending on the task it is commonly useful to prepare some "ready-made" materials—if the design should involve buttons, sliders or dials these design elements can be provided, or if the participants are to design for some specific technology models or examples of this technology should be made available.

Although our examples deal with co-design, the above materials can also be used when asking users to test design concepts generated by the design team. They can also be used to allow users to provide feedback. For example, LEGO has been used for evaluation of maps. In [13] an auditory map was tested by visually impaired persons. When testing how a person understands and remembers a map, it is quite common to ask the person to draw the map from memory after testing the system. If the user is visually impaired this no longer works, and one solution to this problem was to allow the person to use LEGO blocks instead to replicate the map.

Since, as we say in the title of this section, the challenge lies in the activities and the materials, there is really nothing that in principle prevents the involvement of persons with visual impairment in the design of products and/or services aimed for the general public. If care is taken when designing the activities and accessible materials are used, co-design can be made inclusive. In fact, two of the examples above were explicitly made in an inclusive setting and participants involved also persons who were sighted and elderly: Hands-on design workshop and The Mobile Oracle. This leads to our next discussion topic: inclusive design and accessibility.

7 Inclusive Design and Accessibility

When it comes to design intended to be used by persons with disabilities, there are basically three approaches. You can aim for an inclusive design that can be used by "everyone", you can design inclusively for a situation where an assistive device is used, or you can custom make a design (or an assistive device) for a specific user group. While custom-made designs are specifically designed to fit the requirements of a specified user group, an inclusive approach aims to generate solutions that can be used by a wider range of users.

Inclusive design, universal design and design for all are terms that are often used interchangeably, although the terms have different origins and are also used more frequently in different parts of the world. Inclusive design comes from the UK and is defined as “products, services and environments that include the needs of the widest number of consumers”. Thus inclusive design is, as the name says, quite inclusive and goes beyond older and/or persons with disabilities to include also other marginalized or excluded groups. Universal design, on the other hand, originated in the USA and has traditionally a strong focus on the built environment and on persons with disabilities. Design for all finally, is closely related to both the previous terms. Although it started with a focus on persons with disabilities, the EC describes it as ensuring that environments, products, services and interfaces work for people of all ages and abilities in different situations and under various circumstances.

An important advantage with an inclusive design philosophy is of course that you get technology and environments that does not exclude or stigmatize persons or groups of persons. On the other hand, the wide scope makes it unclear “who the user is”. Since it could be anyone, deciding who to involve and how it is done becomes an issue. Thus, human-centred design in this context can be quite challenging. In her thesis [8] discusses how to design inclusively and identifies 13 elements of inclusive design:

- Based on a user (human) centred process
- Organizational commitment towards and knowledge about inclusive design is necessary
- The approach must be holistic, interdisciplinary and context-driven
- Focus on a variety of users and usage contexts
- Involve diverse users early on and throughout the development process
- Facilitate communication between user and developer
- The process must be able to handle different stakeholders, conflicting requirements and changes in requirements
- Ensure conformance to accessibility standards and interoperability with AT
- Focus on a combination of usability and accessibility in context
- Method triangulation: Use more than one method in user research
- Consider using multimodality
- Identity management mechanisms (security, passwords, etc.) need to be inclusive
- Personalization and adaptation may be used to achieve flexibility

When designing activities and materials for user involvement one needs to take common assistive devices into account. Persons with severe visual impairment or blindness typically use the cane (and/or a guide dog) to be able to navigate and avoid obstacles. To access computers, tablets and mobile phones, a screen reader is used. The screen reader can provide output either through synthetic speech or a braille display. Different types of marking systems are also used—e.g. braille printed stickers or more advanced RFID-based tags and reading pens. Persons with low vision may use different types of zooming or enlarging technology.

It is important to remember that not all persons with visual impairment/blindness are skilled at reading braille, and that the majority of the persons with visual impairments are in fact not blind, but actually have use of their vision. Depending on the braille reading skills of a person with visual impairment, sending information and informed consents via email, allowing the person to access the information via the screen reader, may be more accessible than providing printed braille text. Although one can never be certain of which kinds of assistive technology potential users will have, designs aimed at persons with visual impairments need to be designed to work with standard assistive devices. In fact, the ISO 26800 definition of accessibility explicitly includes assistive technologies:

> The extent to which products, systems, services, environments and facilities can be used by people from a population with the widest range of characteristics and capabilities to achieve a specified goal in a specified context of use
>
> NOTE 1. Context of use includes direct use or use supported by assistive technologies.

As we see in this definition, context of use is a part of accessibility, as well as of inclusive design, usability and the general user experience. In the following section we will discuss this more in detail.

8 Context of Use

What a person can or cannot do is dependent on the human and artefactual environment and the interplay between the these. Thus the human and artefactual context plays a key role in determining the success of a design. Simply put, it matters *where, when* and *with whom* activities for user involvement take place. The location dependence was seen quite clearly in the hands-on design workshop example, where focus group interviews sitting down indoors and walking outside yielded quite different results. We do not suggest that *all* design activities need to take place in a realistic context, but it is imperative that at least *some* do.

It should be noted that the office environment, where most of the development and much of the discussion and the design decisions take place, often becomes an implicit and unarticulated reference context for the design. Office spaces are typically fairly quiet, organized and predictable in a way many other environments are not. Using the office environment as a reference is no real problem if the context designed for is similar to an office, but as soon as the intended context of use differs significantly from the office type environment this becomes problematic.

Another implicit design reference is the development situation itself. While much design work takes place during workshops, brain storms and other design activities, as is described earlier in this text, important design decisions are usually also taken by a developer sitting at a desk writing code or constructing hardware. In this situation the developer focuses fully on the artefact, and may be tempted to favour solutions that work well when the user similarly is able to focus fully on the product, but which may work poorly (or not at all) in a context where the user focus needs to be on what they are doing and/or what happens in the environment.

Thus, it becomes important to articulate and reflect on the context of use and to consider how one can bring it into the design process. A thought structure that can be helpful in this process is the "Activity Diamond" introduced by Hedvall [12]. The Activity Diamond can be used to highlight the cultural mediation of (dis) abilities and based on Cultural–Historical Activity Theory (CHAT).

CHAT deals with "the individual in society" and "society in the individual" and how the two co-evolve over time, with contradictions and tensions as the main sources of development.

It has its origins in Russia and the psychologist L.S. Vygotsky's works. According to CHAT, humans and their actions cannot be understood without their mediating cultural tools [7, 18, 39]. Engeström [6] introduced the activity system model, which enables simultaneous analysis of the individual perspective and the collective perspective, portrayed as several simultaneously present activity systems [6]. Targeting the disability field, [12] has further developed Engeström's activity systems model into The Activity Diamond (Fig. 7). The Activity Diamond is a conceptual model aimed at capturing and describing how humans, artefacts and nature mediate and thus influence, i.e. propel or impede, what a person (subject) can do (object). The desired outcome directs the activity. The system is situated [36] in time and place, i.e. in the context of use.

- **The subject** in the model is often an acting individual. On another level, it can be a group of people, such as a family or a community.

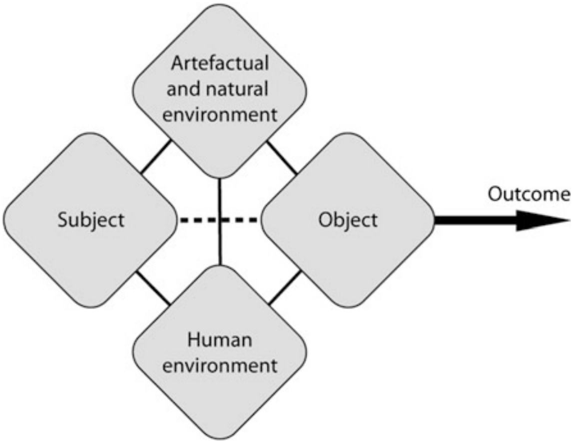

Fig. 7 The Activity Diamond [12]

- **The object** of an activity is related to the motives and needs of the subject, such as getting better grades, learning to read or producing a new car. Thus, the object often consists of or is related to tasks to fulfil or desired goals to reach.
- **The artefactual and natural environment** consists of material and immaterial artefacts, and their respective affordances and resistances. Some examples are computers, language, legislation, air temperature, snowstorms and sunshine.
- **The human environment** is made up of the people or groups of people influencing the activity at hand, such as family, work colleagues or larger portions of society that are involved in or otherwise affect the activity regarding attitudes, norms and expectations.

Hedvall [12] stresses the individual's lived perspective on accessibility. The Activity Diamond analyses how human, artefactual and natural factors impact an individual's possibilities to act in concrete situations that are part of a systemic whole. In design processes the model can be used for discussions regarding who the user is, what the user want to do, and how humans and technology might support this in achieving this desired motive.

Making sure to also involve design activities set in the intended context of use solves part of the problem. In addition, one can consider how this context can be made part of activities that take place in a more lab/office type environment. While personas [10] have been suggested as a tool for user involvement also in activities where no users are present, Context cards [22] have been put forward as one way of allowing varied contexts to be part of activities such as brain storms or focus groups.

9 Conclusion

In this chapter we have discussed human-centred design, and in particular co-design together with persons with visual impairments. We have provided examples intended to serve as inspiration, as well as suggestions for tools and materials that can be used. As is pointed out already by Gedenryd [9] we do not believe that there is such a thing as a design method, in the sense of a recipe that you can follow from the start to the end to ensure good design. What one can (and should) do, is increase the probability of ending up with a successful final product. We suggest that adopting human-centred design is one way of doing this, but we additionally put forward the *mindset* of co-creation something which will allow the design team to not only design *for* the users but also *with* the users. In our experience it is the overall mindset that is the key to success—details of tools, methods and activities tend to fall in place once the design team has a co-creative mindset. Through co-design you gain several advantages:

- by involving future users as an active part of the design team, and by including them on a more equal footing to the rest of the team you open up for the unexpected—when the design team controls what information to gather, only input you expect will be gathered and you miss unexpected, but potentially crucial input.

- you get creative input for your design in the form of inspirational ideas or actual designs.
- you gain an improved understanding of the users, the usage and the context of use.

Our hope is that we in this chapter have provided a reader unfamiliar with co-design with motivation to adopt co-creation as a mindset, and that we have provided inspiration and practical information useful for anyone interested in designing for and with persons with visual impairments.

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Different Approaches to Aiding Blind Persons in Mobility and Navigation in the “Naviton” and “Sound of Vision” Projects

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1 Introduction

Loss of vision deprives the human of a key sensory modality used by humans in spatial *orientation* and *mobility* (O&M). The primary travel aids (the white cane or a guide dog) can help the blind user only in the so-called *micro-navigation* tasks like obstacle detection and avoidance or solving local navigation tasks like recognizing of landmarks or shorelines. However, in new unfamiliar environment, the visually impaired are unable to solve independently the so-called *macro-navigation* challenges, i.e., the tasks of identifying the route and finding a safe way from an arbitrary current location A to a destination point B.

Building an *electronic travel aid* (ETA), whether dedicated to micro- or macro-navigation tasks, has turned out to be a difficult interdisciplinary challenge. The research efforts to build an out-of-laboratory ETA device date back to 1889 when the first attempts were undertaken by a Polish scientist Kazimierz Noiszewski. He built the so-called “Electroftalm” (see Fig. 1), a device that utilized the photoelectric properties of Selenium cells and converted the visual signal to auditory stimulations [62].

The device was heavy and inconvenient to use, therefore did not find any practical application. Unfortunately, one can conclude that more than 100 years

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Fig. 1 Putting the electroftalm on a patient's head [45]

after Noiszewski's Electroftalm and more than 40 years after the attempts made by Bach-y-Rita in the 1970s [1], there is no single ETA device that is widely accepted and used by the community of the visually impaired users [17]. However, the research efforts continue with many, yet partial, successes in the field—see an excellent and comprehensive review of the last decade assistive technologies for the visually and blind people edited by Hersh and Johnson [29].

Most of the earlier and modern ETAs use the concept of *sensory substitution* [42]. A sensory substitution system can be defined as a system that converts the visual modality into acoustic and/or haptic representation. As importantly pointed out in Maidenbaum et al. [42], the neurophysiological mechanism underlying the operation of the sensory substitution systems is that the brain regions can restore their function in vision, even if the stimuli come from an auditory or haptic senses. This is a fundamental observation since more than 90% of visual impairments is not caused by malfunction of the brain regions (i.e., visual cortex), but by defects (e.g., due to illness or an accident) of the visual pathway [68].

A general scheme of a sensory substitution system for aiding the visual impaired in mobility and travel is shown in Fig. 2. The environment sensing module (irrespective of the employed technology) acquires information about the environment that is converted into nonvisual representation for the blind user. If the system aids the blind traveler in micro-navigation, the sensing module provides information on the geometric structure of the local surrounding of the user. If the system plays the role of macro-navigation assistive device, the sensing module provides both the local and global data about the environment, e.g., by means of ground-based (e.g., a network of radio beacons built into environment infrastructure) or satellite based radio-navigation systems (e.g., the GPS system). Those systems are capable of informing the visually impaired user about his/her current geographic position and guide along the preset path to the destination.

The general scheme of the sensory substitution systems applies to the three major types of the ETAs for the visually impaired

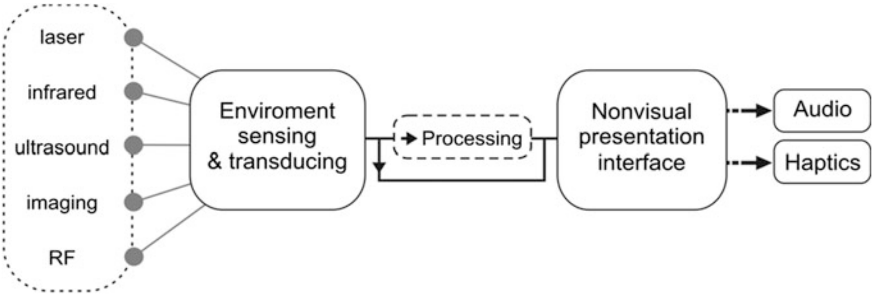


Fig. 2 A block diagram of electronic travel aid (ETA) system employing the sensory substitution concept (in simpler ETA solutions the processing block denoted by a dashed line is optional)

1. *Obstacle detectors*—handheld small devices or devices attached to the white cane [15]; it was postulated by Loomis [40] that proximal stimulation, e.g., vibration of a white cane can induce perceptual impression of objects in external space, this phenomenon was termed distal attribution and has been investigated in later studies [58],
2. *Environment imagers*—imaging systems employing computer vision technologies to convert scene images into other modalities [10],
3. *Navigation systems*—different ICT-based technologies using, e.g., embedded infrastructures, GPS navigation systems, urban travel aids, or teleassistance systems [5, 36].

The first two classes of aids are personal (wearable) devices aiding the micro-navigation tasks within personal and near spaces. The third group of aids includes systems that offer macro-navigation support for the blind user.

In this chapter, we review the prototypes of sensory substitution systems for the blind, which have been made in the Institute of Electronics of the Lodz University of Technology. Many of the solutions were tested and evaluated by blind individuals. The assistive devices that were developed are reviewed in this chapter according to the introduced ETA categories. The environment imagers are

- *Sonified stereovision system for local navigation*—a wearable device incorporating stereovision module and for detecting and warning of the obstacles employing stereovision;
- *Haptic interface*—a device allowing to build haptic maps of the environment intended to be used as a training aid for the visually impaired, which can be defined as environmental imagers using employing imaging techniques for 3D scene reconstruction and auditory or haptic nonvisual presentation techniques;

and the navigational systems adding the visually impaired are:

- *A network of radio beacons mounted in urban infrastructure*—the network aids the visually impaired in more precise positioning in indoor areas and improves GPS positioning precision outdoors, e.g., locating public transport stops,

- *Public transport information module*—employing a server storing online information about location of public transport vehicles;
- *Dedicated applications for smart phones equipped with speech synthesizer*—serving as a navigation aid capable of informing the user of nearest points of interest (POIs) and routing pedestrian paths to indicated destinations;
- *Teleassistance systems*—a solution enabling a person located at a remote terminal (stationary or mobile) to guide visually impaired individuals by monitoring transmitted life images of the path in front of the blind traveler, which in turn can be classified as navigational systems aiding the visually impaired.

2 Sonified Stereovision System for Local Navigation

An ETA wearable solution that we proposed for local navigation and obstacle avoidance utilizes stereovision input and an auditory output. It was intended to be a midpoint between environmental imagers and obstacle detectors, i.e., simplified scene imaging and reliable obstacle detection. Figure 3 explains the key concept of this approach. Stereovision images are processed and analyzed to build a 3D model of the environment. The detected obstacles (within the radius of 4 m) are coded by a set of sonifying parameters characterizing the shape, size, and also the orientation and location of the obstacle versus the observer.

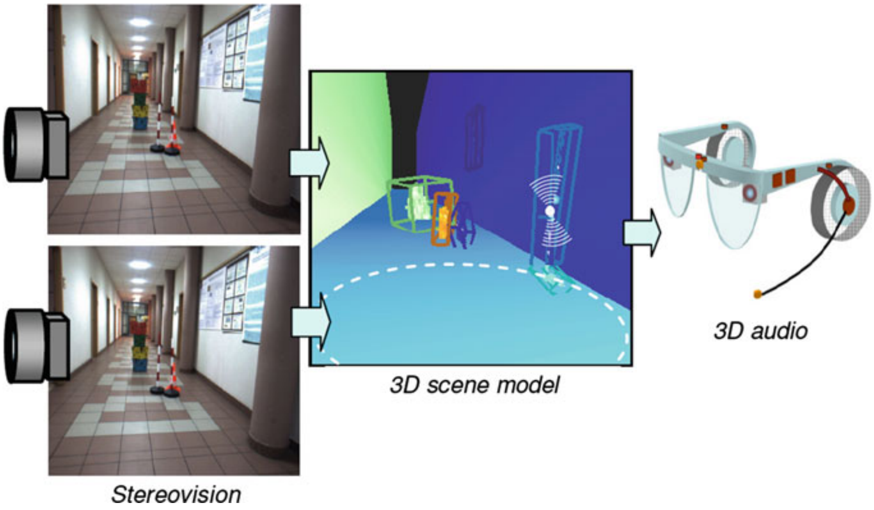


Fig. 3 The "Naviton" ETA concept [10] for local navigation and obstacle avoidance: stereovision is used as the environment sensing module, its two output images are used to compute a simplified 3D model of the observed scene, which is then sonified using spatial audio

2.1 Environment Sensing Subsystems

From the possible methods of scene acquisition, stereovision was chosen as the best choice that could offer both portability and high resolution. Stereovision is a passive method for environment depth sensing which does not use any internal light source and works properly in both outdoor and indoor environments.

A wearable stereovision system as shown in Fig. 4 was designed and built as an environment sensing module for the electronic travel aid (ETA) for the blind [53]. The module, which is housed in a case resembling large glasses comprises a pair of RGB cameras, a six DoF (*Degrees of Freedom*) inertial sensor and a custom-designed two-channel sound card.

The geometry of the optics of the stereovision camera is shown in Fig. 5. An important condition for a proper reconstruction of the scene depth is a correct calibration of the stereovision system so that the so-called *canonical setup* of the system is achieved, i.e., the corresponding rows of pixels in image sensors in the left and right camera are collinear. Moreover, geometric distortions of both cameras must be identified and corrected for each of the captured images of the environment [41].

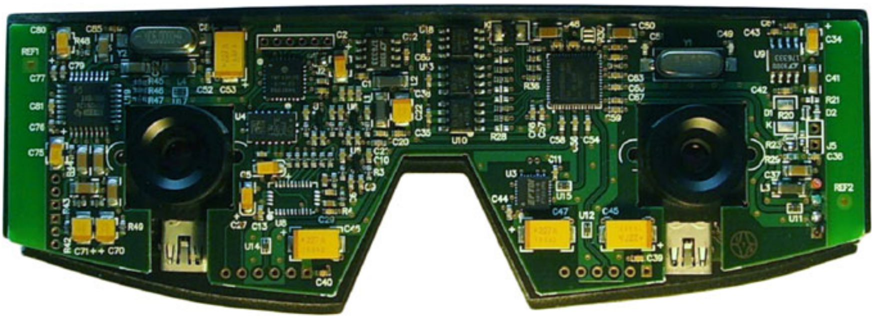


Fig. 4 Electronic module comprising a stereovision system and a sound card; the distance between the optical axis of the cameras (camera baseline) is $B = 60$ mm

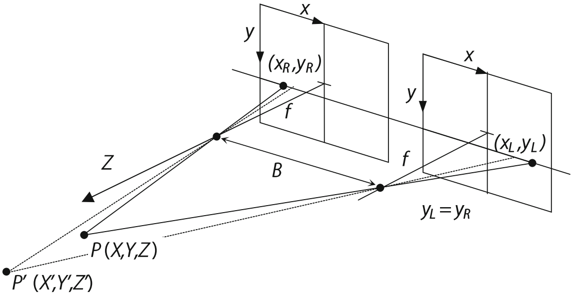


Fig. 5 Stereoscopic system in a canonical setup

Fig. 6 Three-dimensional reconstruction of the "corridor" scene from stereovision: **a** left (reference) image, **b** right image, **c** depth map is pseudo-colors (the *color palette codes the depth of the scene objects; warm colors* represent objects in close proximity whereas *cool colors* represent distant objects)

To calculate a dense depth map, which gives information about the Z-coordinate (depth) of each scene point seen by stereovision cameras, the disparity for each point in the image must be calculated. Disparity $d = x_L - x_R$ can be defined as the difference in the position x_L and x_R of the same point P visible in both images and can be efficiently calculated using the *Block Matching* (BM) technique [60]. The relation between the disparity d and the depth Z which is the distance along the Z-axis of the camera is given by a hyperbolic dependence $Z = Bf/d$ where f is the focal length of the camera and B is the baseline. Figure 6 shows a pair of stereovision images of the scene and the depth map shown in pseudo-colors. Depth map shows the Z-coordinate of each point visible in the reference image captured by the camera in the camera coordinate system. This distance is coded using greyscale or pseudo-color values.

A 3D geometric scene model is built form the obtained depth map. The proposed scene model consists of the two categories of elements: *surfaces* (especially the surface of the ground) and *obstacles*. Surfaces tend to be very important sources of information for the visually impaired and blind users and can be described using the plane equation. In order to determine the surface descriptions, we proposed an iterative algorithm which is based on the comparison of normal vectors found in regular triangle mesh in the depth image [59]. The result will be a scene which is divided into two types of regions: planes and other objects. The objects assume 3D coordinates that do not fit any of the detected planes—thus, they are interpreted as the obstacles (see Fig. 7a). On this basis the geometric scene model is rendered from the OpenGL 3D modeling software as shown in Fig. 7b. Note, that only the obstacles within a distance of three meters from the blind user are reconstructed and detected by the system.

The detected planes are described by plane equations. Having calculated the normal vectors of the planes it is possible to identify ground surface and wall surfaces. The detected objects, on the other hand, are described by a set of geometric parameters defining location, size and spatial orientation of a cuboid circumscribing the object—see Fig. 7b [59].

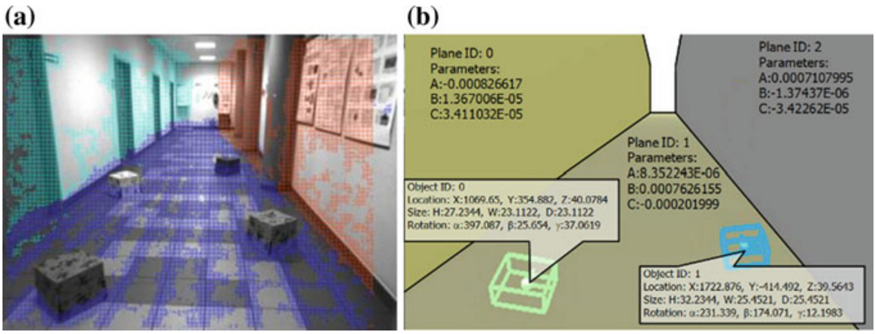


Fig. 7 **a** Model composed of the detected planes and other objects (obstacles), **b** the OpenGL 3D render of the scene

From the generated models we have also built the so-called *occupancy-grid* representation of the 3D scene (see Fig. 8). This visualization technique allows to define the scene areas devoid of obstacles. This information is of key importance for the sonification algorithms used for auditory display of the environment for the blind user of the system.

2.2 Auditory Display

Simple monosonic alerts were present in the early ETAs designs [20, 33]. The sounds later developed to two-channel stereo [34] for basic 2D acoustic imaging of blind person's visual surrounding [14]. Human's hearing is however far more advanced than a simple left–right pair of microphones. The sonified output of the

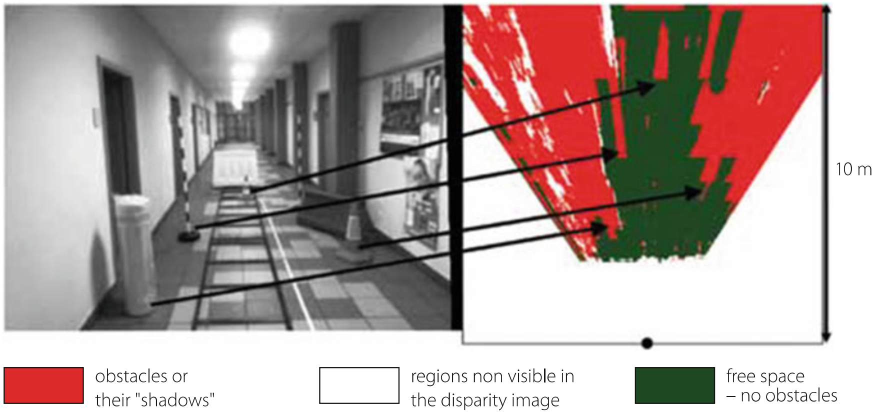


Fig. 8 An occupancy grid of a three-dimensional scene calculated at floor level

proposed “Naviton” ETA [10] was spatial audio, so extensive research in this direction was made. Sound source location is identified by distance and direction. Distance perception depends mainly on the sound pressure level—the louder a source is, the closer it appears to the listener. Determination of direction is more complex.

The most frequently listed phenomena and factors contributing to the sense of direction are [50]

- Interaural time differences (ITD),
- Interaural level differences (ILD),
- The filtering action of the human body (i.e., outer ears, head, shoulder, and torso), which makes ITD and ILD a function of direction and frequency,
- The ratio of the reverberant versus directly received sound energy,
- Familiarity of the listener with the sound source,
- Changes in sound due to head movement.

The importance of interaural effects is clearly seen in the superior accuracy of horizontal (i.e., left to right) over vertical (i.e., top to bottom) source localization [16, 19].

When considering a spatial audio based wearable ETAs, the basic idea is to use a pair of stereophonic headphones and artificial ITD/ILD synthesis, which should allow to create at least horizontal illusion of sound directionality. This method however cancels the natural sound propagation effects introduced by the nearby parts of the human body (outer ears in particular), which may deteriorate the localization accuracy or, in case of vertical location sensing, even render it impossible. A more advanced technique that simulates the human body filtering effects is based on the application of *Head-Related Transfer Functions* (HRTFs), determined for different sound source directions and describing the dependence of ILD and ITD on the direction and frequency of a sound [13, 15]. Determination of the HRTFs is however a complex process as they are significantly dependent on the individual anatomical features of a given listener. Different approaches are in use

- Full individualization—direct HRTF measurements for every listener [12, 40, 42],
- Empirical HRTF selection from an existing database [24],
- Analytical HRTF calculations based on generic head/torso model [42],
- Modeling based on generic HRTFs and anthropometric data [44, 46–48],
- Modeling based on 3D finite element method simulations [12, 42],
- No individualization—application of generic (dummy head) HRTFs.

Individualized HRTFs provide better localization performance, the measurement procedure is however difficult, time-consuming and demands specialized equipment (see Fig. 9). Localization errors such as “in-the-head” perception, front-back confusions or elevation shift can still be present in listening tests, but techniques such as headphone equalization, head tracking, and reflection rendering can significantly improve the spatial audio experience [10, 11, 16, 18, 21].

Fig. 9 Equipment for fast measurement of individual HRTFs

2.2.1 Headphones

Another factor to consider when designing auditory output for a device to be used by blind persons are the headphones. Even open-type headphones significantly attenuate external environment sounds. While the “Naviton” project used high-quality reference headphones for all the listening tests, including pilot trials of the prototype, part of the “Sound of Vision” project [61] is to choose, or design, a suitable headphone that does not impair normal hearing of the wearer, but still allows the spatial audio perception.

In the Sound of Vision project, selected headphones were compared in order to determine which would deliver the best spatial audio. The compared headphones included: full size reference open-air supra-aural headphones as a high-quality control group, bone-conduction headphones that press against the temples and do not cover the ears, in-ear “secret service” type headphones that utilize small rubber tubes that push the sound into the ear canal without blocking it, and finally a custom prototype with four proximaural speakers (see Fig. 10). The headphones were tested with 10 volunteers in standard listening trials with static virtual sources and various spatial audio solutions—generic HRTFs from the MIT KEMAR database [24], individualized HRTFs measured at TUL [16], constant energy stereo panning and “quadrophonic” panning for the multi-speaker prototype [66].

In terms of average azimuth errors, all headphone types produced similar results, ranging from 16° to 18°, with the reference headphones and the custom prototype providing the most reliably accurate localization. The custom headphones had a very good localization accuracy only for “low-resolution” tests where sources were 60° apart. The average elevation errors (cf. Fig. 11) were very high regardless of the headphone type and spatialization method used, and ranged between 19° and 39°, while the expected error for random guessing would be 48°. The high-quality reference headphones gave the best results, with individually measured HRTFs providing only a marginal improvement over the generic ones. While the in-ear air tube headphones tended to be the worst, the bone-conduction headphones showed the most variability—for some users they were the best type overall, for some the worst. The custom headphones performed on par with the reference headphones, well enough to warrant implementation in the planned “Sound of Vision” prototype [61] and further research on the subject.

2.2.2 Sonification Methods

Sonification, defined as the delivery of information through a nonspeech audio, is widely used in ETAs for visually impaired people. The ETA applications range from basic obstacle detectors to complex environmental imaging systems. The

Fig. 10 Prototype proximaural quadrophonic headphones for generating spatial audio without blocking environmental sounds

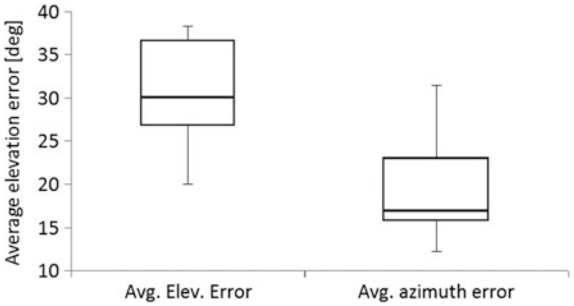


Fig. 11 Average absolute elevation and azimuth errors for the custom quadrophonic headphones prototype in a virtual sound source localization task (5 × 7 grid, every 30°)

existing and proposed ETA solutions differ in how they collect information about the surrounding environment and how they present it to the user by means of sonification. Input for an ETA may come from:

- “Simple” range sensors, e.g., active (emitter + receiver) ultrasound, infrared, laser [19, 20, 30, 33, 34, 42, 49],
- Multiple combined range sensors [52, 57],
- 2D video camera, which may be supplemented with an additional range finder or GPS/GIS information [21, 38, 47, 56, 69],
- Stereovision cameras [2, 10, 18, 26, 27, 47].

The sonification aims at transforming the input environmental information to a possibly intuitive aural impression. Known sonification techniques include

- Direct or inverse distance to pitch and/or loudness transform [20, 33, 42], with optional binaural amplitude variation adding directional information [34, 57],
- Instead of continuous sound of varying pitch, binaural clicks of varying repetition frequency [52] or discrete musical tones and/or rhythmic patterns [19, 20, 26, 30, 38, 49] can be implemented,
- Mono- or stereo-inverse spectrogram, where rows and columns of an analyzed 2D or stereovision image are coded with sound frequency components [2, 38, 47, 56],
- Spatialized (HRTF) virtual sound sources (Gonzales-Mora [18, 27], additional reverb adds distance information [21],
- Stereophonic auditory icons with loudness coding distance [69],
- Forward traveling scanning surface emits discrete sounds as it hits the obstacles and varying pitch and decaying loudness along continuous surfaces [10].

Simple ETAs based on discrete sensors have their functionality limited to signaling the user of an obstacle they are pointing at. On the other hand, the quantity of information delivered by sophisticated environmental imaging systems requires substantially more focus and training from the user and often results in tiredness in case of prolonged usage [25].

2.2.3 Sonification Methods in the “Naviton” and “Sound of Vision” Projects

The very first sonifications tested in the “Naviton” project resembled those found in the ETAs utilizing simple range sensors, with range represented by inversely proportional musical tones, i.e., the smaller the distance the higher the note. The environment was probed or “scanned” with these “musical range finders” producing sequences of notes (see Fig. 12).

Progress with the 3D reconstruction and segmentation leads to another possible sonification approach—assigning sounds to segmented scene objects. These sounds would convey various parameters of each object, such as direction and distance to observer, category (e.g., wall, stairs, car) or size. The object sounds could be spatially filtered to appear to originate from appropriate positions in the scene and could be presented in various order (e.g., of proximity) or be independently looped.

These sonification approaches were tested as computer simulations with two groups of 10 volunteers each, the first normally sighted, the second blind. The surveys conducted during the tests led to several conclusions that were utilized in later designs [10]. Among them were

- Availability of several sonification modes for a user to choose from, e.g., more narrow obstacle detection for travel, wide scanning for scene orientation,
- Preference towards discrete musical sounds, over continuous frequency changes,
- Preference for familiar musical instrument sounds over artificially sounding tones, such as a synthesized glottal tone,
- Pauses between delivery of consecutive sound sequences,
- Markers indicating start/end of a sequence of sounds.

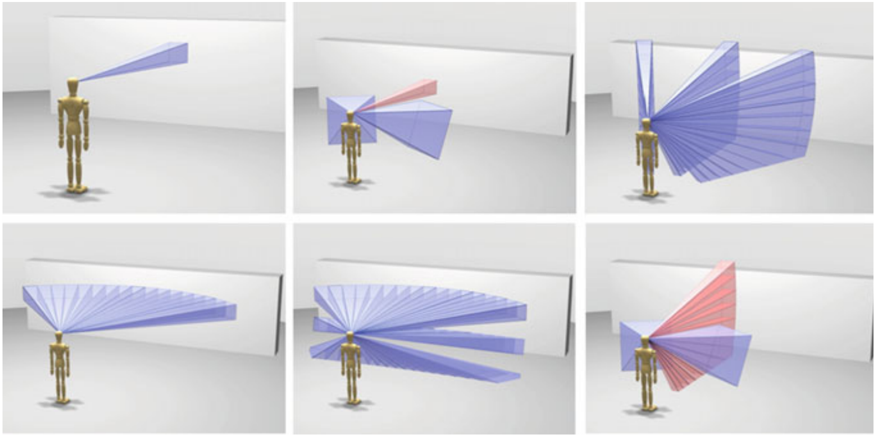


Fig. 12 First trials of the “musical range finder”—the environment was scanned with various patterns and a sound corresponding to the nearest obstacle in each cone was played

The “Naviton” project ended with a pilot study of a portable prototype that utilized a stereovision camera, scene reconstruction, segmentation that divided scene objects into walls and generic obstacles, and HRTF filtered output. The sonification scheme used in the prototype, inspired by sonar and dubbed “depth scanning” (see Fig. 13), was as follows:

- The observed scene was segmented into walls and generic obstacles of approximated height and width,
- A virtual scanning plane parallel to the camera image plane moved away from the observer along the camera axis (the default settings was that the plane moved 4 m in 2 s cycles),
- The movement of the scanning plane was signified by four progressively quieter percussive ticks, every 1 m,
- Whenever the scanning plane intersected an object, a virtual sound source corresponding to that object was played back and tracked in real time,
- Each sound source was spatially filtered with individualized HRTFs to appear to originate from the corresponding object’s center of mass,
- The sound’s pitch and loudness were inversely proportional to the distance and duration was proportional to the object’s width,
- Walls were assigned a separate category of sounds with lower pitch and different timbre, their sounds were also usually longer as they lasted as long as the scanning plane intersected them.

The “Sound of Vision” project inherits a lot of concepts from the “Naviton” project, such as the general concept of segmenting the 3D scene into objects, starting by detecting large surfaces and generic obstacles, with the possibility of more specific categorizations (e.g., detecting stairs, cars, humans) and assigning sounds to said objects.

So far four sonification models have been proposed and tested by the “Sound of Vision” consortium. Two models are inspired by the “Naviton” sonification—one is the depth scanning model, the second is a variation of it, except that the scanning surface sweeps left to right from −45° to 45° azimuth. Two are completely new.

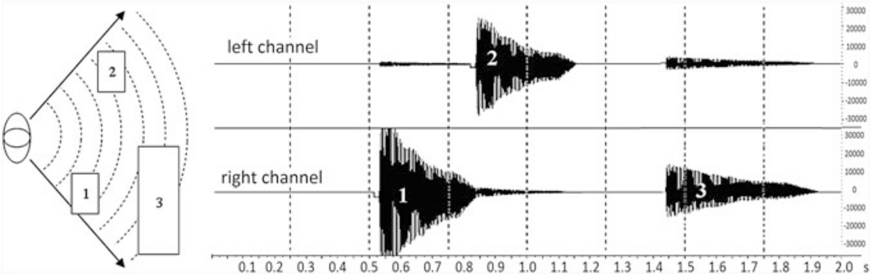


Fig. 13 The concept of “depth scanning”—sound sources corresponding to scene objects are released in order of their proximity and spatialized to appear to originate from the obstacles

The first one assigns repeated impact sounds (virtual sound sources) to each object. The sources are ordered left to right in azimuth, but the number and intensity of repetitions correspond to the distance to an object, while the width is factored into the frequency of the sound. The second divides the observed scene into three regions: left, center, and right third, each 30° wide. And quickly plays back three sounds corresponding to these regions. If a region is empty, a quiet "heartbeat" sound is played, if there is at least one object in range, the closest object is responsible for the sound properties. The sound is lower for wider objects, and the loudness signifies distance.

2.2.4 Tests and Results

The Naviton sonification was tested by five blind and five blindfolded volunteers, each group consisting of two women and three men, in a controlled environment, i.e., with cardboard box obstacles color coded to aid segmentation. The volunteers tested the efficiency of obstacle detection, avoidance, and orientation in a safe environment. Trial times, collisions, and verbal scene descriptions served as objective results.

The tests were designed to provide simultaneous training and thus progressed in complexity and difficulty. After introductory 5 min. instructions the participants learned through the tests themselves, completing ten tasks in each test. The first trial consisted of identifying the location of a single sonified obstacle, pointing to it with a white cane, then walking over to touch it. The second trial was similar, but for two obstacles. The third and fourth trials consisted of walking towards a speaker 5 m away from the observer, while avoiding two and four obstacles in the respective trials. The results are presented in Tables 1 and 2.

Travel speeds are considered a poor measure of an ETA's efficiency, as their use frequently increases safety at a cost of travel time [29], but the gathered data allowed for some observations and conclusions. The blind participants also provided valuable subjective feedback. The participants needed to hear on average two scan repetitions (2 × 2 s.) to determine the position of a single obstacle and three 2 s. repetitions for three obstacles. As they explained, the additional "looks" were needed to verify if the object sounds correctly corresponded to their initial impression. Although the prototype trials utilized personalized HRTFs, four of ten participants stated that they perceived little to none spatial audio externalization; however, as they progressed through the trials they began to subconsciously associate the sounds with external sources. The volunteers also moved very slowly, it took on average 30 s to reach a target that was five meters away. This was likely due to the instructions to minimize the use of the white cane (holding it vertically) and clearly announce any contact with an obstacle beforehand (otherwise it was counted as a minor collision) (Fig. 14).

Table 1 Task completion times and error rates in “Naviton” prototype trials

Trial no.	Task	Static localization				Dynamic travel		
		Average task time [s]	Standard deviation [s]	Direction error rate (%)	Distance error rate (%)	Direction error rate (collision)	Distance error rate (collision)	Path choice error (collision)
1	Localize a single obstacle, walk to it	4.1	1.2	4	9	4% (3%)	8% (4%)	–
2	Localize two obstacles, walk to the second	5.4	1.3	4	4	6% (0%)	6% (4%)	–
3	Navigate 5 m path between two obstacles	24.5	7.0	–	–	3% (3%)	4% (4%)	2% (0%)
4	Navigate 5 m path between four obstacles	33.5	13.7	–	–	0% (0%)	4% (4%)	11% (6%)

Table 2 Error types in "Naviton" prototype trials

Navigation and travel errors (out of 100)	Trial 1	Trial 2	Trial 3	Trial 4
Incorrectly chosen path	–	–	2	11
Lost orientation	–	–	1	0
Minor collision due to the chosen path	–	–	0	6
Minor collisions due to misjudged direction	3	0	3	0
Minor collisions due to misjudged distance	3	4	4	4
Missed target due to misjudged direction	3	6	–	–
Missed target due to misjudged distance	5	2	–	–

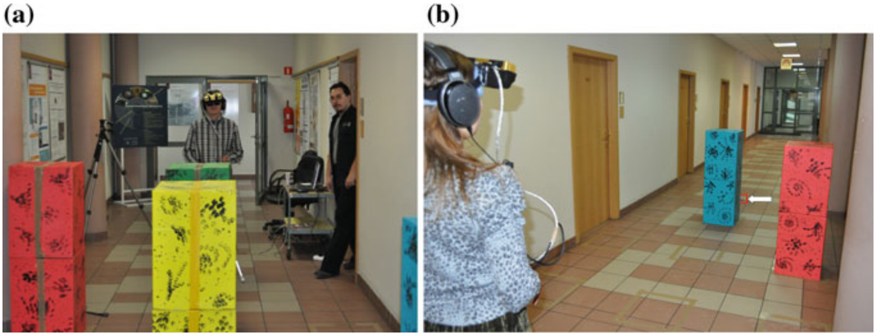


Fig. 14 "Naviton" prototype trials in a controlled environment. Blind (**a**) and blindfolded (**b**) participants first localized, then navigated between cardboard obstacles to reach a sound source (indicated by a white arrow in a photo on the right)

3 Haptic Display Techniques

It was shown in many studies that touch, apart from hearing, is another modality that can be used to substitute vision in spatial perception. The early prototypes by Noiszewski [62], Bach-y-Rita [1] and later by Bourbakis [9] showed potential usability of tactile vision substitution systems. Recently this line of research has been actively developed by Pissalox and coworkers [43, 54, 65].

A seminal study on using haptics for exploration of the environment was initiated also in the "Naviton" project. A haptic space presentation system was built in order to enable the blind persons a touching interaction with 3D real objects created in virtual reality. The prototype (Fig. 15) consists of the "Mesa Imaging SR3000" ToF (*Time of Flight*) camera, a laptop and a "Falcon Novint" haptic interface.

The ToF camera computes the distance from obstacles in a scene by measuring the time of flight of the emitted and the light reflected back. A depth map (where depth values are represented as colors, cf. Fig. 16a) is built at the output. The depth map is segmented in order to detect the obstacles and create a virtual scene of the environment (Fig. 16). "Falcon Novint" haptic game controller is used for a tactile exploration of the virtual scene. Using the sense of touch the blind user accesses

Fig. 15 A haptic interface bench. From left to right: model cardboard scene, 3D computer model of the scene, haptic interface programmed to simulate the virtual scene

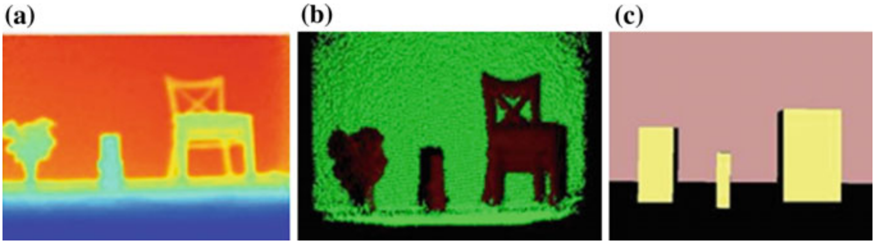


Fig. 16 The virtual scene modeling process: **a** 2.5D depth map of the scene, **b** the segmented scene, **c** the obstacles are replaced by cubes [51]

information about the content of the observed scenes. The system usability was examined by eight blind participants [51]. The tested scene was rendered by a haptic representation in a scale reducing of the scene size by a factor of 38. The achieved precision (maximum error) of the rendering (related to real scene scale) was 15 cm. The blind participants were able to successfully count the obstacles and describe their spatial distribution. With an increasing number of the rendered objects, however, the time required for haptic exploration tended to increase substantially and reached 4 min with an average time of 3 min for four rendered objects. A possible application concept of a personal haptic interface is shown in Fig. 17.

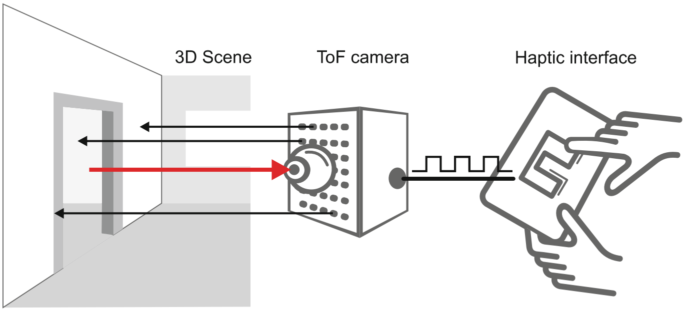


Fig. 17 The concept of haptic display of the environment using the ToF camera and a personal haptic interface

4 Teleassistance Systems

The concept of telenavigation is relatively new and provides many advantages and new research directions. The main idea behind the teleassistance relies on transmitting video and audio stream from a blind person's terminal to a sighted remote operator (the guide). Basing on the video data, the guide can navigate the blind traveler by spoken instructions that are sent back through an audio channel. In most cases, the visually impaired require help on just a few occasions and then can proceed on their own. Hence, the solution affords more privacy and autonomy in comparison to a traditional seeing guide.

4.1 Review of Teleassistance Systems

One of the first researches on teleassistance systems was reported in [23]. The researchers conducted a study where a blind user wore a UHF (Ultra High Frequency) camera, GSM phone for voice communication and GSM modem for relaying GPS coordinates. A PC terminal displayed on the map the traveler's location and a video stream. The trials described successful guidance within the university campus. The UHF video transmission was restrained to several dozens of meters.

Subsequent research [32] employed the GSM technology to transmit all necessary data, thus providing assistance almost from any place.

As the GSM bandwidth is not suitable for sending online video streams of adequate frame rate, the researchers in Garaj et al. [22] undertook a study on the effectiveness of teleassistance under a limited frame rate. The results are somewhat counterintuitive. The researchers claimed, that the effectiveness of navigation was independent of the frame rate within a range of 2–25 frames/s. Lower frame rates caused, however, the remote operator to get fatigued, as the navigation required more mental effort to anticipate situations.

Study [37] proves effectiveness of teleassistance in shopping. Other attempts to build telenavigation systems for the blind are reported, e.g., in [4].

4.2 Proposed Solution

The system developed at the Lodz University of Technology is presented in Fig. 18a. It is composed of a mobile terminal worn by a blind person and remote terminal (e.g., a PC computer) operated by a sighted guide.

The mobile terminal is a small one-box device housing a camera, IR LED for night mode, headset, GPS receiver, HSPA GSM modem, keyboard with big convex keys and processing unit. The photo of the terminal is shown in Fig. 18b. The device is operated through speech-synthesized menu. The camera lens is of wide field of view (ca. 90° horizontally), as compared to the field of view of mobile phones being around 20° The video, GPS coordinates and the battery status are sent through the GSM Internet, which introduces transmission delays. The voice can be transmitted either through dedicated GSM audio channel, thus not experiencing delays, or Internet data channel, which is usually cheaper.

The remote guide is equipped with a dedicated PC application which allows to observe the video stream from the blind person's terminal, see the geographical

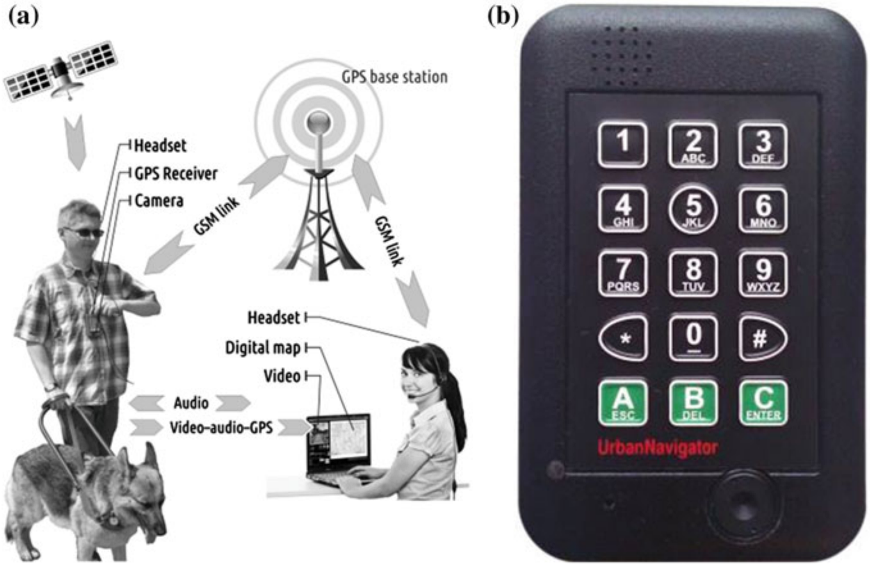


Fig. 18 Proposed telenavigation system: **a** simplified diagram, **b** photo of the mobile terminal

location and walking direction of the traveler, monitor the battery level of the mobile terminal and what is important watch the video transmission delay. The application is shown in Fig. 19a. The remote guide can in run-time change the resolution of the camera between 160 × 120, 320 × 240, and 640 × 480, whereby lower resolutions provide faster frame rate and higher facilitate reading details like textual information. The guide can also assist blind itinerants using a mobile phone or tablet running on Android operating system—see Fig. 19b. More details are available in Baranski and Strumillo [6].

4.3 Results

The system effectiveness was validated through the emphatic trials, where seven sighted individuals (aged 26–55, five men and two women) took the role of blind itinerants. The participants were not blindfolded, however were told to follow literally the guide's instructions. The tests were carried out at the university campus and based on traveling from one place to another. Each participant had to cover three unknown paths, all ca. 370 m in length. An example path is shown in Fig. 20. During the walk, the following events were noted down: walking duration, missteps, minor collisions, lost ways, lost connections. The results are summarized in Table 3. The average walking speed with the remote guide equaled 2.44 km/h and was compromised mainly by lost connections. By comparison an average walking speed in a straight line for a sighted individual is 4.5 km/h.

Fig. 19 Proposed telenavigation system: **a** PC application of the remote guide, **b** the application running on an Android mobile phone

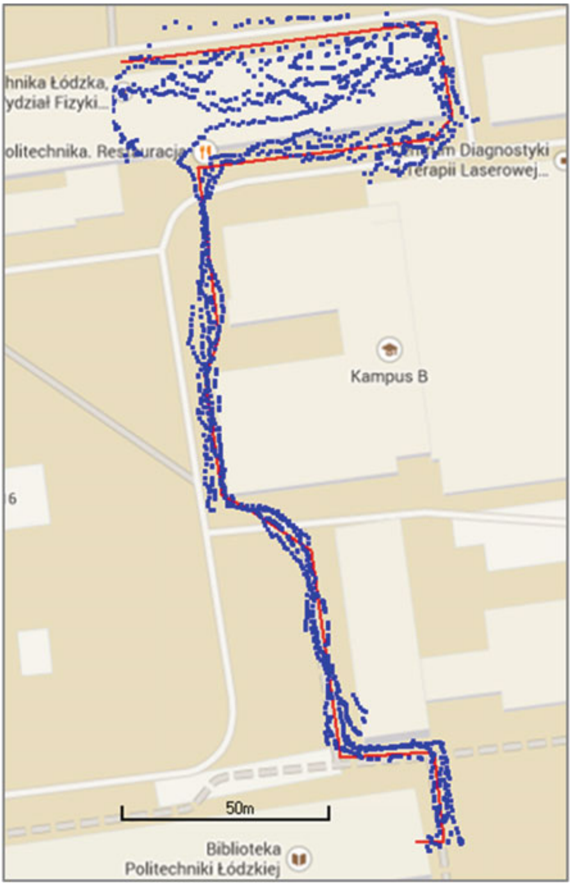


Fig. 20 An example path of 371 m length. *Red solid line* denotes the path followed; *blue dots* show GPS readouts

The conducted trials corroborated the effectiveness of the teleassistance concept, both in macro- and micro-navigation. Telenavigation systems can be helpful in learning new paths. In many cases, only short navigation sessions are sufficient to help a blind person to travel on their own (e.g., crossing a street, finding a button activating green-light for pedestrians, getting back on the track when lost). The users of the system should be aware of the transmission parameters, determining the transmission delay and quality of the video. The new, dynamically developing 4G LTE (*Long-Term Evolution*) technology should provide better quality of service, especially in urban areas.

Teleassistance improves on GPS navigation in many aspects. In urban areas, GPS readouts tend to be inaccurate—up to several dozen of meters [5]. The remote guide can on the base of the video ascertain the traveler location and navigate him or her precisely to the destination.

Table 3 Aggregated data for three paths

TP	TP1	TP2	TP3	TP4	TP5	TP6	TP7
Duration (min)	29.3	24.8	27.4	28.5	26.2	21.5	36.1
Avg. speed (km/h)	2.26	2.66	2.41	2.31	2.52	3.07	1.83
Missteps	1		1			1	
Minor collisions		Parked car 1			Parked car 1		
Connection lost	2			1			4

The total traversed distance was ca. 1.1 km for each participant. TP stands for trial participant

5 Navigational Aids

Majority of contemporary systems use *global navigation satellite systems* (GNSS) receivers to estimate actual user location [55]. Due to multipath propagation and strong attenuation of radio signals in the urban environment, the positioning errors may reach 100 m [64]. One of the ways to enhance the positioning accuracy in urban areas is to deploy in the environment a network of embedded low power, short-range radio beacons that can be used to indicate the proximity of the user to a given *point of interest* (POI), i.e., a place of a special significance to the user. Exemplary beaconing systems such as PAVIP [8], Step-Hear [63] and URNA [7] use infrared or radio transmitters to indicate various classes of POIs.

5.1 Naviton Radio Beacons

The framework of the guidance system developed within the “Naviton” project consists of dedicated applications, database servers, a network of radio beacons, and user terminals. The general architecture of the proposed solution is shown in Fig. 21.

The application servers store data required for given services, i.e., a database of POIs or timetables of public transport vehicles, and manage the communication between system components.

A network of short-range radio beacons located on bus stops, public transport vehicles, entrances to public buildings, etc., provides high accuracy location information at places of possible interest to the user. The transmitters periodically send unique identifiers that can be decoded by the application server and used to provide the user with additional context-related information.

The core structure of the systems can support a variety of user terminals ranging from off-the-shelf mobile devices, e.g., smartphones or tablets, to dedicated electronic travel aids tailored to the specific needs of visually impaired users.

The prototype guidance system comprised a network of battery operated radio beacons operating in 868 MHz unlicensed frequency band (Fig. 22). The core element of the device is Texas Instruments CC430 family ultra-low power

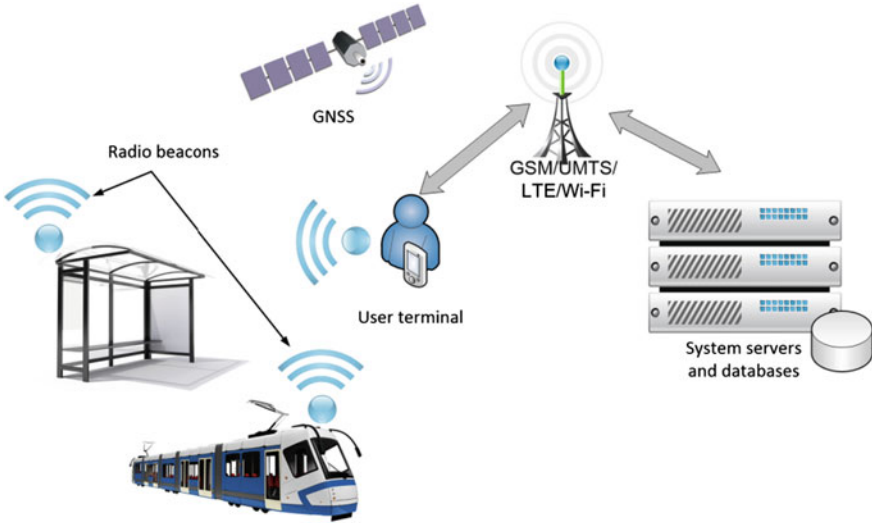
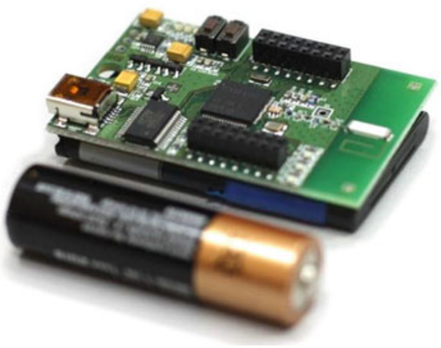


Fig. 21 Architecture of the distributed system for guiding the visually impaired

microcontroller managing integrated radio transceiver core. Depending on the POI category, the beacons send unique messages with transmitting power levels ranging from −30 to +12 dBm. The adjustment of the transmitting power is used to meet different requirements regarding the expected coverage of the beacon. For example, at the tram stop the beacon coverage is limited only to the zone where the user can safely wait for the vehicle. On the other hand, transmitting range of the beacon indicating the vehicle approaching the stop is set to higher level to give the user enough time to prepare for getting on. The beacons can also send messages with multiple, sequentially changed power levels.

Fig. 22 Radio beacon prototype built for system tests



5.2 *"POI Explorer"*

One of the usage scenarios of the guidance system assumes the use of standard off-the-shelf smartphones as user terminals. The contemporary mobile devices equipped with GNSS receivers, motion sensors, and multiple wireless communication interfaces provide a good basis to serve as terminals for visually impaired users [14]. To verify the suitability of modern smartphones to the needs of guidance of visually impaired users, a "POI Explorer" application was developed [35]. Also a dedicated remote controller was proposed to facilitate the control of key functions of the mobile device.

"POI Explorer" is an application for Android operating system aiding the visually impaired in independent travel. Its functionality has been worked out with the target group of users. It uses standard Android components, which allow to cooperate with available screen readers, e.g., "Google TalkBack" [28]. Some advanced navigation modules are prepared using graphical mode with the use of *Text-To-Speech* libraries. Such solution allows to easily navigate through the menus, while advanced modes for communication with the user can use the vibrations, voice commands, and sounds. "POI Explorer" allows to navigate the blind users in different modes. In the first mode user can be navigated along previously prepared paths or to the selected point, like shop, bus stop, etc. The distance to the waypoint or to the endpoint is calculated based on readings from the GPS receiver. Direction to the point is presented in the per hour mode. Orientation is determined based on a compass sensor and based on the history of the GPS values.

The look around mode is especially dedicated if users move around unfamiliar areas. You can get a list of POIs from the selected categories within a defined radius. For each of the points the distance and the direction are estimated. If user selects a destination point, our application will automatically switch to the navigation to the specific point mode.

To simplify the use of the application special sonified mode was proposed. User can search for POIs in his neighborhood. A virtual circle is moving away from the user's location. When it crosses the POIs location, a short sound assigned to the given category is played. User can stop scanning to hear detailed description of the point. Application navigation in this mode is based on the 3D gesture detection. Gesture detection module uses gyroscope, accelerometer, and gravity sensor.

The remote controller visible in Fig. 23 is used to control the "POI Explorer" mobile application. One can navigate through the application menu and choose the designated option without the direct use of the phone; it can be hidden in the user's pocket. Connection between the device and the mobile phone uses the Bluetooth interface.

The second task of the remote control is detecting and reading data from the radio beacons scattered in the environment. The messages read from the beacons can then be further processed by the "POI Explorer" application to offer additional location-based- and context-aware services.

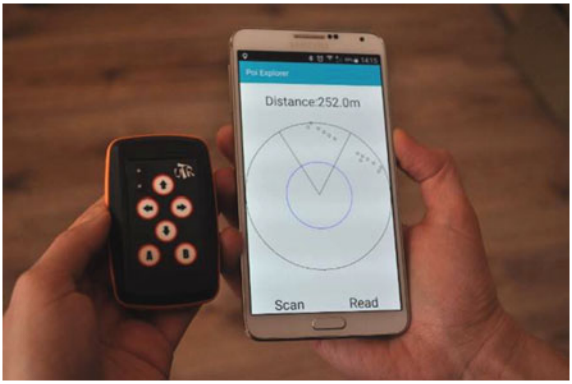


Fig. 23 “POI Explorer” in a sonified mode working on Galaxy Note 3 Android phone. Each *dot* visible in the screen marks point of interest from the address category. The small device on the left is used for controlling (via a Bluetooth link) the “POI Explorer” application

The system developed within the framework of the “Naviton” project has been applied to support visually impaired users in using public transport services [36]. Having an online access to servers processing information on public transport routes and timetables, as well as actual locations of trams and buses enables a variety of applications of the proposed distributed guidance system.

To make the best use of the data from the passenger information system, several extensions to the “POI Explorer” application were developed. The additional functionalities include route planning and providing the user with actual location aware information on public transport vehicles approaching the bus/tram stop. The latter functionality makes use of identifiers broadcasted by radio beacons located on vehicles and bus/tram stops.

5.3 Results

The positioning accuracy of a network of radio beacons was evaluated in one of the university campus buildings [67]. The layout of the test premises along with beacon installation points is presented in Fig. 24. The radio beacons were set up to transmit packets with output power ranging from −30 dBm in a proximity detection mode to +10 dBm in a coarse localization mode. When the beacons transmit signals with low power, the position of the user terminal can be approximated by the known location of the transmitter. This approach is called proximity detection and can be used to inform the user of reaching given POI. When beacons transmit signals with higher output power, the signals can be used to roughly estimate the user position. During the system evaluation, we used the so-called received signal strength indicator (RSSI), a fingerprinting technique which relies on assessment of the similarity of received signal strength indicator (RSSI) measurements reported by the

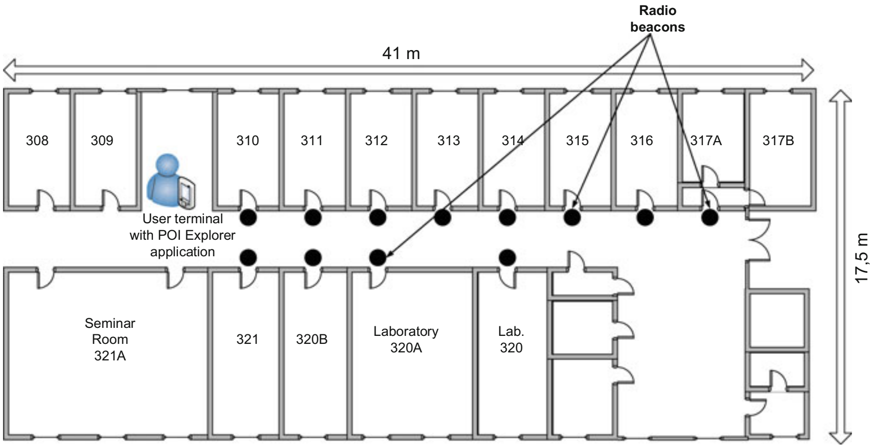


Fig. 24 Proximity detection tests—test site with radio beacons (*black dots*) indicating entrances to office rooms

Table 4 Summary of coarse localization results

Criterion	Result
Percentage of correct entrance detections	29.8%
Mean positioning error	4.47 m
Median positioning error	2.38 m

terminal to the some predefined reference data recorded in predefined locations and stored in the system database. Table 4 summarizes the results of coarse localization with the use of the database correlation technique.

6 "Sound of Vision" Project: Natural Sense of Vision Through Acoustics and Haptics—Concept and Current Status

"Sound of Vision: natural sense of vision through acoustics and haptics" [61] is research project funded by the European Commission under the Horizon 2020 framework programme [31]. In this section, we present the project concepts and discuss the key aspects that distinguish it from other attempts to create assistive solutions for the visually impaired.

6.1 Concept and Functionality

“Sound of Vision” aims to design, implement, and validate a noninvasive, wearable solution (hardware and software) that will assist visually impaired people by creating and conveying an auditory and haptic representation of the surrounding environment. The main processing steps and its basic components of the system are represented in Figs. 25 and 26.

The input of the system is represented by a head-mounted hybrid stereo + ToF 3D acquisition system, including also inertial measurement unit (IMU). As in the “Naviton” project, the raw 3D scene data is to be segmented into distinct objects, corresponding to the entities from the environment. Furthermore, a few classes of objects that are extremely relevant for perception and navigation are identified separately, such as the ground, walls, stairs, doors and ground-level obstacles, and holes. Based on this analysis and classification of the 3D environment, a synthetic model of the environment is created.

The synthetic model will be conveyed to the user using a parallel audio and haptic encoding (sonification and haptification). The audio rendering will use spatialized audio and the haptic rendering will use a vest with a matrix of vibrating motors and possibly vibrating bracelets. Additionally, the “Sound of Vision” system will take a pragmatic approach to attempt to detect possible dangerous situations, such as predictable collisions or falls, in which case the user will be alerted. The alerts will be different from the normal rendering. Another feature of the system will be scanning for recognizable text and if possible, reading it through text to speech. In addition to the device itself that will be created by the project, a set of comprehensive accompanying training programs will be also created. Furthermore, intensive user evaluation tests are part of the project in order to validate the design.

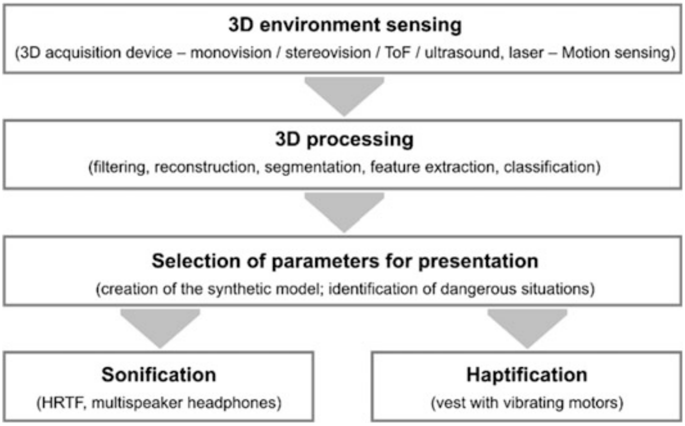


Fig. 25 Basic processing stages of the “Sound of Vision” system

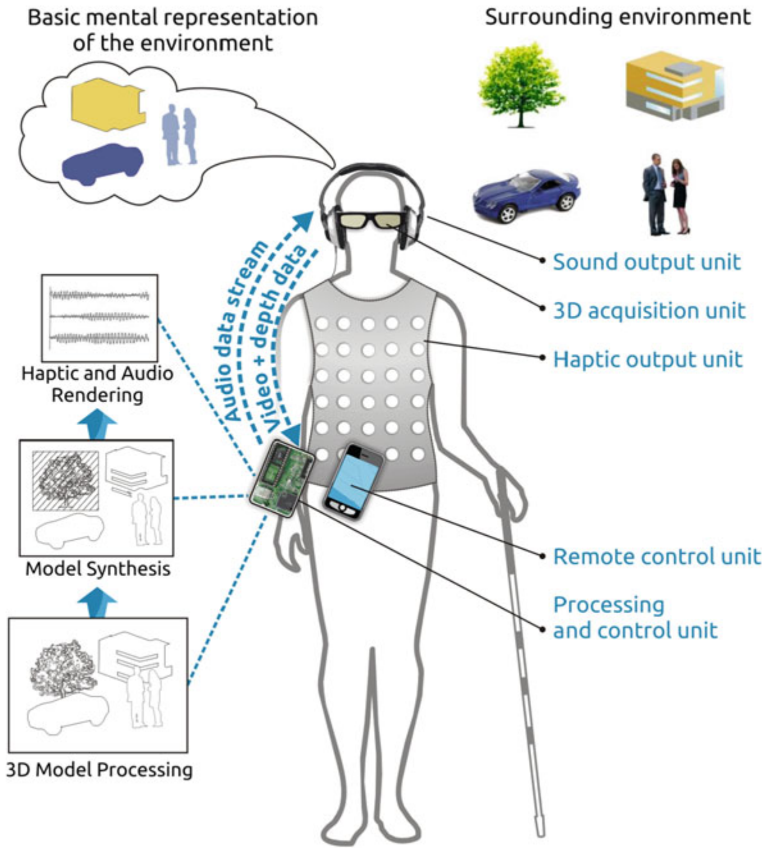


Fig. 26 Basic components of the “Sound of Vision” system [61]

During some of the tests techniques such as psychophysics, EEG and more will be used to help identifying functional adaptations of users resulted from the usage of the system.

6.2 Key Prospects

Some key aspects that distinguish “Sound of Vision” from most of the previous approaches are

- Artificial sense: the focus on creating a new, artificial, cross-modal sense, allowing the user to “feel” the environment, rather than providing just navigation support and obstacle detection.
- Dual correlated rendering, both audio and haptic.

- Strong navigational support, both through detection of dangerous situations and texts.
- Naturalistic encoding: significant effort will be dedicated to make the developed artificial sense as similar as possible to the natural sense of vision, and at the same adapted to the specifics and limitations of the substituting modalities (hearing and tactile).
- Unprecedented focus on training: in order to help the user achieve performance in understanding the provided audio-haptic representation, "Sound of Vision" will develop a set of training procedures based on real and virtual training environments. In particular, the virtual training will make extensive use of gamification, specifically, serious games, with the goal to provide high degrees of immersion, motivation, and fun for the visually impaired trainees. This will stimulate them to train for significant amounts of time, with good focus, and thus achieve high performance. It should be noted that the very few experiments [38, 39] which attempted training with sensory substitution solutions, even basic ones, with less or no naturalness, achieved very promising results. Initial experiments performed by the "Sound of Vision" project [3] proved that even simple forms of training, without gamification elements and complex scenarios, and even for short duration, can help trainees develop abilities to understand and use sound based encodings of environments.
- Interdisciplinary team: the consortium includes high caliber specialists in assistive technologies, computer vision, acoustics, wearable devices, electronics, neurosciences, eHealth and, most importantly, organizations representing the end users and caretakers.

6.3 Current Status

The project started at the beginning of 2015 and already has completed its first two stages, out of five.

The first stage focused strongly on obtaining information (through interviews, questionnaires, and reviews) from the end users to elicit, refine, and optimize the requirements. An assessment of the current stage in the base technologies needed for the prototype (such as stereo and ToF cameras, haptic actuators and drivers, audio headsets, and mobile processing units) was performed. Starting from these, the system architectural design was created.

The work in the second stage was concentrated on implementing and testing alternative techniques and components in order to be able to make selection for the first prototype. The work included 3D scene modeling and reconstruction (filtering, reconstruction, segmentation, features extraction, classification), testing and comparing different off-shelf headphones for delivering spatial sounds, creating and testing custom headphones for delivering spatial sounds, creation and testing of sonification models and clearing out the most of the technological risks. A detailed perspective on the training was provided, through the design of a complex serious game concept.

Furthermore, as both the development of the device itself and the accompanying neuroscientific studies rely heavily upon testing, dedicated testing environment, including both real and virtual environments, as well as customized data collection tools, were designed and created.

7 Summary and Conclusions

In this chapter, we have focused on reporting our different research approaches to building electronic assistive devices for supporting the visually impaired in orientation and mobility. Our key efforts were directed towards building human–machine interfaces (wearable or embedded into the urban infrastructure) to help the persons with visual disability in such tasks as space perception, obstacle avoidance, and navigation in unfamiliar environments. They reported

- Wearable sonified stereovision system enabled auditory presentation of 3D scenes so that the blind users could maneuver and omit obstacles in laboratory setting,
- Haptic display system proved useful in helping the blind users to build a cognitive map of the environment with possible future wearable implementation,
- Teleassistance system, that relays video from the location of the blind user to a remote guide, underwent first successful trials and shows, in our mind, the most promising solution assisting the visually impaired both in local and global navigation,
- Network of radio beacons embedded into the urban environment and public transport vehicles proved efficient in playing the role of navigation buoys informing the user about his/her whereabouts that outperforms the GPS in localization precision,
- “POI Explorer” mobile application, can communicate both with the beacons playing the role of POIs, identify its locations on a map and perform user auditory interface.

Reporting on the above technological successes on the ETA prototypes we are aware that these achievements are humble successes, which are still far from being ready solutions for guiding the visually impaired in real-world indoor or outdoor environments. We see these technologies rather as bases for virtual reality or real-world training environments. From our rich interactions with the visually impaired we conclude that that developing an adequate, user-centered scheme for training in efficient use of the ETA is of paramount importance. The requirement for user training is strongly highlighted in the “Sound of Vision” EU project.

Finally, we believe that our work is yet another path strengthening multinational and multidisciplinary efforts in overcoming many barriers the visually impaired people face in their social and professional life.

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Overview of Smart White Canes: Connected Smart Cane from Front End to Back End

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1 Introduction

There are 285 million visually impaired people (VIP) worldwide, among whom 39 million are blind [1]. Numerous Electronic Travel Aids (ETAs) have been developed, but most VIPs still use a white cane for their displacements and as a symbol indicating that they are blind or have low vision. The white cane cost, ease of use, and safety are among the reasons of its popularity. However, this assistive tool has several limitations and its concept should be revisited, especially in the presence of new digital technologies.

In this chapter is presented the state-of-the-art of ETAs by focusing on their functionalities, hardware architectures, and integration of Information and Communication Technologies (ICT), such as Cloud computing, Internet of Things (IoT), and smartphone. Connected Multi-Input Multi-Output ETA—called MIMO eETA—will improve the blind safety by providing more relevant environment perception. Therefore, MIMO eETA will significantly improve VIPs' well-being by easing their mobility and quality of life.

This chapter is divided into four sections: first, is introduced general knowledge about VIPs, their mobility, and a classification of electronic devices used to help

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them in their mobility. The second section is dedicated to the description of a new concept of such tool, the eETA, with the description of its desired functionalities: obstacle detection, navigation and guidance, and support to environment perception. The third section exposes the current state of the implementation of an eETA, its architecture, and related experimentations. Finally, the back-end tier is analyzed: its specifications, functions, and implementation are described in the fourth section.

1.1 Main Features of VIP Mobility

Mobility and orientation are the biggest challenges for VIPs: according to Manduchi and Kurniawan, 6% of blind people never go outside of familiar routes, 34% once a month or more, 45% once a week or more, and 15% once per day or more, since walking without sight brings forth the risk of loss, falls, and collisions [2]. One way to improve VIPs' quality of life is to develop assistive technologies to ease indoor and outdoor environment explorations and interactions.

Mobility encompasses at least two synergetic tasks[1]: walking and orientation. The walking skill is the ability to safely move from one place to another. It means being able to walk without hitting obstacles, without tripping or falling, to cross roads and to use transportation means, in particular public ones. The orientation skill is one's ability to self-localize in space and to assess different places with respect to his/her current position [3]. Orientation may imply the usage of a mental representation of a spatial map.

VIPs have a limited capacity to walk safely, since they hardly sense obstacles on their way without assistance. Their ability to know where they are and how to reach a target location is also limited, since they can only use a limited amount of information to identify and recognize places. Therefore, they are only able to build limited representations of their environments with respect to the representation a sighted person is able to build [4].

ETAs are supposed to provide minimal but necessary information for mobility. Lévesque (2008) presented a good survey on the ETAs assisting obstacle detection and allowing the blind to find a safe and clear path [5]. Existing classifications are only based on the output information of ETAs: devices providing complex or basic information. To meet the evolution of ICT, a new classification of ETAs should be elaborated by considering their inputs, outputs, connectivity capabilities and their integration with IoT, cloud computing and mobile networks. These new technologies offer not only opportunities for new services such as near real-time VIP navigation and assistance, but also a perception of the world closer to that of sighted people.

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[1] Cf. Part 3 of this book on mobility cognitive models.

1.2 Environment Perception by VIPs

The knowledge of the environment is essential for human mobility and orientation. Before taking decisions relating to their mobility and orientation, sighted people establish a mental mapping of spaces mainly through the visual channel [6]. They tend to consider a representation of space as a visual experience. Vision appears to be the best sensory channel for the acquisition of spatial information because it provides a relatively simultaneous perception of large spatial fields [4]. Other sensations and actions such as hearing, smelling, touching, and moving can also provide perceptual information about the environment.

VIPs—especially congenitally blind people—have enhanced auditory acuity and very sensitive haptic and olfactory senses. Integrating multiple perceptual experiences, they can progressively construct a mental map of spaces through the acquisition of spatial patterns [7].

However, there are differences between the perception of space by sighted people and VIPs. In the latter, remoteness or closeness is not measured by distance (in meter or km), but by step count (as a pedometer). German philosopher and physician Ernst Platner (1744–1818) even concludes that, for congenitally blind people, distance means a longer or shorter trip time to reach the objective, as distance means a longer trip time to reach the objective. Furthermore, spatial representation may be built with different cognitive patterns: VIPs usually constitute their space representation from a “path structure”, while sighted people frequently use “spatially related landmarks” [4, 8].

Blindness onset has also impact on space representation. Studies carried out on early blindness and perceptual developments do not produce unanimous result [4, 9–13]. However, they demonstrated the ability to form mental spatial models in congenital, early and late blind people. Most of these studies come to the conclusion that “early blind people have lower performance in spatial tasks than late ones, especially in displacement representation and spatial inference” [4, 10, 11, 13]. Indeed, the sensorimotor intermodal coordination established during the first years of life is beneficial for late blind people [14]. This coordination allows their spatial performance to be closer to that of sighted people. However, both early and late blind people prefer local, path-based information for spatial representation and strategies, and use the exploration movement-based coding mode for localization inference. Such behavior can be explained with the type of information obtained under blindness, which is different from that obtained with vision. Path-based representation is better suited and more efficient for blind people, as it is easier to exploit without global vision. The existing ETAs support the path-based approach to the mobility.

1.3 Classification of ETAs

Nowadays, to assist blind people in their everyday life, different tools are available, such as white canes, guide dogs, and ETAs. The estimated average lifetime of a guide dog is 5–8 years and its average cost is around 30 k€ for acquisition and 5 k€ for annual maintenance over the animal's working life [15].[2] In USA, only 0.5% of legal blinds own a guide dog [16]. For VIPs, low cost, robust, and easy to use ETAs appear to be a more appropriate general solution.

Several classifications of ETAs already exist,[3] all only based on the type of output information provided to the end user (e.g., voice, sound and vibration). Each ETA belongs to a class ranging from I to IV.

Class I devices have a single point-wise output for object preview (vibration or sound to indicate the presence of an obstacle).
Class II devices have multiple outputs for object preview (point-wise information on object is provided from multiple directions); it is a secondary aid or primary tool.
Class III devices have object preview, plus environmental information by giving text rather than headlines.
Class IV devices provide previews of objects, plus artificial intelligence [16].

This classification does not highlight ETAs' hardware and software architecture features such as robustness (e.g., space and time redundancy) and overall real-time performance. Moreover, it does not consider the services that may be provided by ITS (Intelligent Transportation System: traffic light informs the blind of its status), IoT (smart object informs its location and use), and Cloud (e.g., itinerary and hints when the blind is lost). A new generation of ETAs (eETA-connected ETA) can provide more accurate and reliable environmental information by exploiting multiple information sources and communication channels. We therefore propose a new classification of ETAs that takes into account the number of both local and remote (e.g., cloud server) input and output information channels in order to provide an overview of the complexity of each ETA in term of hardware and software organizations. As a result, this new classification enables, for instance, to estimate the robustness of obstacle detection (e.g., multiple sensors are used to detect obstacle) and ETA connectivity for orientation efficient assistance (connectable or not to a network). For each connectivity class, three sub-classes of ETAs have then been identified according to their input–output capabilities: Single-Input-Single-Output (SISO), Multiple-Input-Single-Output (MISO), and Multiple-input-Multiple-Output (MIMO). Each of these classes is briefly characterized hereafter.

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[2] http://www.ncbi.nlm.nih.gov/pubmed/18432492.

[3] See also Part 4 of this book.

1.3.1 Single-Input-Single-Output (SISO) ETAs

The first generation of unconnected SISO ETAs mainly focused on the obstacle detection using 1D range sensors: ultrasonic, infrared (IR), and laser sensors.[4]

Most of the available ETAs are based on ultrasonic sensors; this choice was made due to the simplicity of their use, low cost, and acceptable range detection (e.g., 15.2–600 cm). The principle of operation is to use ultrasonic echolocation to detect objects at varying distances. Ultrasonic waves are elastic waves typically ranging between 40 and 180 kHz that propagate in solids, liquids, and gases [17]. The distance of an obstacle may be estimated by measuring the Time of Flight (ToF) from a transmitter to the obstacle and then, after reflection, back to the receiver located near the transmitter.

Equation (1) provides means to estimate the distance d (m) to a point of an obstacle located in front of the end user and the speed v (m/s) of ultrasonic wave propagation in the air in function of its temperature T:

$$\begin{aligned} d\,(\mathrm{m}) &= \frac{v * ToF}{2}\,; v\,is\,the\,velocity\,of\,ultrasound \\ v\,(\mathrm{m/s}) &= 331.4\sqrt{1+\frac{T(^{\circ}\mathrm{C})}{273.15}}\,where\,T\,is\,air\,ambiance\,temperature. \end{aligned} \tag{1}$$

The first handheld ETAs based on ultrasounds were developed by Russel [18] and Kay [19]; Russel's device indicated whether the path was clear or not, while Kay's device directly communicated distances to obstacles as sound pulses. A more recent handheld ultrasonic ETA is the Miniguide with a push button to change the mode of operation. It detects obstacles at five different distances, referred to as operating modes [20]. This device vibrates to notify the user of obstacles in its immediate environment. The vibration frequency increases when the distance of the object decreases. The Mowat Sensor is another handheld ultrasonic-based device that informs the user of the distance to detected objects by means of tactile vibrations [21]. However, as materials such as cloth, cotton and wool absorb ultrasounds, obstacle detection using ultrasonic waves is not completely reliable.

Infrared sensors overcome some limits of ultrasonic sensors; they are widely used as proximity sensors and for obstacle avoidance in robotics [22]. Figure 1 outlines the principle of IR scanning of the environment. An IR receiver captures the reflected light and the voltage is measured based on the intensity of received light, which enables to estimate the distance of the object.

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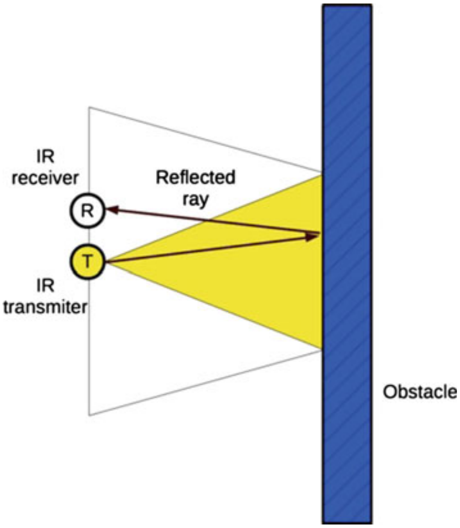
[4] Although "laser" and "infrared" refer to different, independent aspects of light, and as such cannot perfectly discriminate sensors, we use the terms "infrared sensor" and "laser sensor" in their common sense: an infrared sensor uses an incoherent beam of infrared light, whereas a laser sensor uses a single coherent beam of light, visible or not. Furthermore, we call "laser sensor" only the sensors measuring the distance on a single point; we refer to higher dimensionality laser sensors (2D, 3D) as "LIDARs".

Fig. 1 Principle of IR scanning of the environment



"Tom Pouce" is a handheld ETA detachable device that can be attached to a cane. It is based on several near IR beams (950 nm wavelength) generated by collimated LEDs, in different directions and at different emission powers, in order to cover a "protected" area [23]. When the received photoelectric signal is greater than a fixed threshold, the device vibrates to alert the blind to the presence of an obstacle. Tom Pouce has three running modes for three detection distances: 50 cm, 1.5, and 3 m. Notice that IR sensors are sensible to the sunlight and, as with ultrasonic sensors, the intensity of the reflected waves depends on the obstacle properties (surfaces have different scattering, reflection, and absorption properties). The typical response time of IR is 2 ms. The distance measurement has globally 20% of uncertainty (around the length of one step).

Like ultrasonic distance sensors, laser distance sensors measure the time-of-flight to estimate the distance between the emitter, the obstacle, and the receiver. Teletact 1 is a handheld laser telemeter that has been developed at the University Paris 11. It has two output alert channels: tactile vibrations and sound [23]. According to the obstacle distance, a signal is emitted: a sound from 6 to 15 m, a light vibration on a finger from 3 to 6 m, a strong vibration from 1.5 to 3 m, and a strong vibration on another finger below 1.5 m. The accuracy of the estimated distance of the obstacle is about 1% for distances ranging from 10 cm to 10 m.

The point-wise environment scanning obtained with laser, ultrasounds, and IR requires the VIP to remain strongly focused in order to discover the whole shape of the detected obstacle and to elaborate the avoidance procedure. This complex space integration task can be facilitated by object detection and recognition using image technologies. The basic steps of object recognition, once it is localized, are the following: image capture, features extraction, features grouping, feature matching, or classification.

Thanks to the tremendous advances of smartphones in terms of cost and computation power, a lot of research has been carried out using the smartphone camera as an ETA input sensor for obstacle detection and recognition [24–26].

According to the field test results published by Foerster et al. [24] and Tapu et al. [26], cameras are not accurate enough to be used as SISO ETAs, for any type of obstacle. However, identification of a known specific object (e.g., traffic light signaling, door) using a camera gives acceptable results. For example, Yusro et al. [27] used a smartphone camera to detect the status of traffic lights and inform the VIP through audio output. Figure 2 illustrates the block diagram of the system, and Fig. 3 its flowchart: image acquisition and processing on a smartphone (color filtering and thresholding) and audio data generation for a VIP.

Lin et al. [28] showed that doors, door handles, and door plates may be detected and recognized (Figs. 4 and 5) with an ORB feature detector running on a Raspberry Pi board (Rev. B); the processing time was about 40 ms for each frame.

Considering their widespread use and powerful abilities, it is likely that the role of smartphones as an input device of ETA for obstacle detection, human–machine interface (HMI), router, etc. will be more and more important in the coming years.

In the case of eETA, more precision may be obtained by sending raw images to friends or to the remote cloud server to get help, because CMOS camera are sensitive to changes of environmental parameters such as light intensity and the color of the obstacles compared with the ground one.

Fig. 2 Block diagram of the system for traffic light status communication to a VIP

Fig. 3 Main step of the image processing on the smartphone for traffic light status discovery

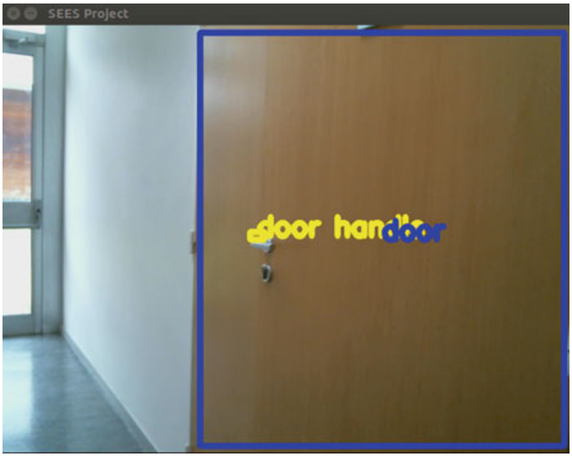


Fig. 4 Door handle detection with image processing running on a Raspberry Pi B board

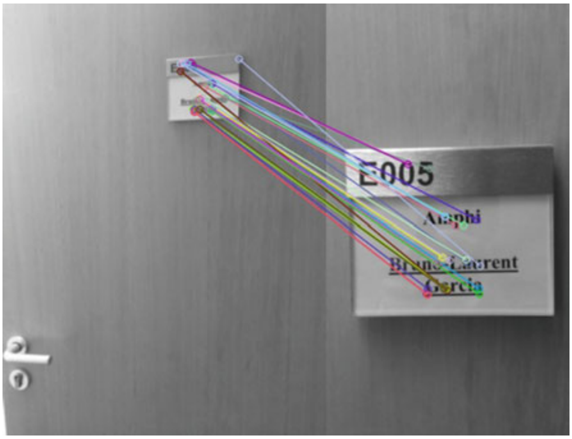


Fig. 5 Doorplate detection using the ORB feature detector running on a Raspberry Pi B board

1.3.2 Multiple-Input-Single-Output (MISO) ETAs

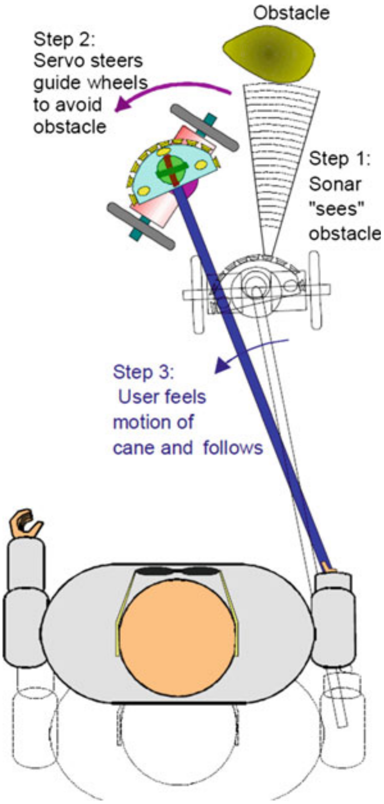
As already said, SISO ETAs are not able to deliver reliable information concerning the presence or not of an obstacle and require an important cognitive effort in order to extract all characteristics relevant to obstacle avoidance. An alternative would be to use several—heterogeneous or homogenous—sensors in an ETA. MISO ETAs use several sensors to enhance the efficiency and accuracy of obstacle detection and navigation. Input sensors are usually a mix of the sensors used in SISO. Based on this approach, several systems have been designed.

Like Teletact 1, Teletact 2 is based on a laser telemeter; however, it adds an infrared proximity sensor to provide more reliable results. In both systems, the human–machine interfaces are either tactile or sound-based [23].

The NavBelt is based on a belt equipped with eight ultrasonic sensors subtending a 120° solid angle of the space, the end user being the apex of this angle. The NavBelt is able to detect the presence of obstacles, and stereophonic headphones inform the VIP about the status of the environment. After 10–20 h of self-training, users have been able to travel at 0.6–0.8 m/s while avoiding obstacles as small as 10 cm in diameter [29].

The GuideCane is a motorized wheeled cane (Fig. 6). A steering servomotor, operating under the control of the GuideCane's built-in computer, can steer the guide wheels left and right, relatively to the cane. Attached to each guide wheel is an incremental encoder, and an array of ultrasonic sensors is mounted in a semi-circular fashion above the guide wheels. A digitally controlled fluxgate compass is also mounted above the guide wheels. The embedded computer uses the data from encoders and from the fluxgate compass to compute the relative motion of the traveler—by means of odometry, as well as the instantaneous travel speed. A miniature joystick that can be operated with the thumb allows the user to indicate a desired direction of motion [30]. The GuideCane may be equipped with a GPS receiver to provide global positioning information within 20 m accuracy. Haptic

Fig. 6 GuideCane: operational space [30]



feedback indicates the path: the devices turns and brakes to avoid obstacles, which the user can feel through the handle.

Stereo rigs provide depth estimation measures; they are intensively used in robotics and smart cars to perceive environment, mainly for obstacle detection and avoidance, and for object recognition [31–33]. Lazaros et al. [34] presented a good survey on the stereo vision algorithms, taking software and hardware into account. However, in general, the authors do not consider the energy consumption of stereo vision for object detection and recognition, which is a key constraint for wearable and portable systems. Another problem is its dependence on environmental characteristics: scene illumination, scene surface characteristics, scene object density, etc. Reliable real-time stereo vision for obstacle recognition and avoidance is still an open research issue.

According to the current state-of-the-art, the performance of stereo vision is not reliable enough to be used as a single sensor of a MI ETA, but it may occasionally be used as a part of a MISO ETA combined with other sensors for object recognition and obstacle avoidance to minimize energy consumption and increase the accuracy of object detection. In the case of connected MISO ETAs, stereo images could be sent to the cloud server for more complex processing implementation (e.g., object recognition, 3D scene reconstruction).

1.3.3 Multiple-Input-Multiple-Output (MIMO) ETA

In order to make an ETA reliable, flexible and easy to use, having multiple inputs and outputs is a key issue. Several MISO ETA presented above may further evolve as MIMO ETAs; for instance, the NavBelt becomes a MIMO ETA once it offers both tactile and stereophonic outputs to inform the VIP about the status of the environment.

Notice that output interfaces of ETAs such as coin vibration motors, sound, speech synthesis, and tactile braille will be more and more affordable in terms of cost, energy consumption, and space. Therefore, it is possible to integrate them in new ETAs.

1.3.4 Summary

Nowadays, available unconnected ETAs (SISO, MISO, and MIMO) do not appropriately fulfill VIPs' needs, particularly those of blind people, in terms of obstacle detection, recognition and avoidance, navigation, and assistance.

The next sections will present an example of eETA, a connected smart cane, which can significantly improve VIPs' perception of the environment. Moreover, VIPs may be guided remotely in near real time everywhere worldwide, and they can get help when needed.

1.4 Connected ETA (eETA): Concept and Proposed Architecture

As we pointed out previously, most blind people worldwide still use a simple white cane for their displacements because the current available unconnected ETAs do not provide expected functionalities and dependability. This section introduces the concept of a MIMO eETA and its implementation into a connected smart stick.

1.4.1 Concept of a MIMO eETA

A MIMO eETA is an electronic device dedicated to assisting VIPs with their mobility and able to communicate with the surrounding world—other devices included—via a set of sensors and information outputs.

Sensors, which often can be seen as electronic ersatz of physiological sensitive organs, provide data describing the external world according to their perceptual capability. Cameras (in visible or IR spectrum), ultrasonic range sensors, and GPS chips are example of frequently used sensors (MIMO eETA inputs). Speech synthesizers, touch-stimulating surfaces (such as Braille keyboards), and vibro-tactile stimulators are the most popular examples of information outputs. They provide data that can be used either by humans or other electronic devices. MIMO eETA sensors and information outputs are able to communicate both between each other and, through the network, with the external world.

1.4.2 Proposed Architecture of a MIMO eETA

A MIMO eETA can be implemented in a distributed manner, in three components (Fig. 7):

- The front end is a white cane equipped with sensors allowing it to perceive indoor and outdoor environments (also named a Local MIMO Smart Cane or “LMSC”);
- The smartphone is a kind of local server, as it provides offline server-like services, e.g., maps repository. Furthermore, it plays the role of router and of human–machine interface;
- The back end is a dedicated cloud computing platform for VIP guiding and assistance in near real-time worldwide.

It should be stressed that the smartphone can be enhanced by a device designed to communicate with VIPs, such as a touch-stimulating surface.

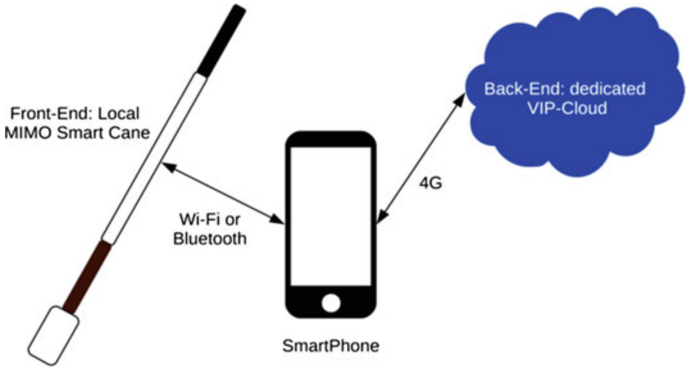


Fig. 7 A white-cane-based MIMO eETA

2 Design of a MIMO eETA Based on a White Cane

This section presents in details the concept of a MIMO eETA. It starts with an overview of an academic prototype named 2SEES, and then addresses an overview of the available technologies for the design and implementation of a future MIMO eETA.

2.1 2SEES: An Academic Prototype of a Connected Smart Stick

2SEES (pronounce “to SEE”) is under joint development by a consortium composed of LIMOS (CNRS/Clermont-Auvergne University, France), University of Rouen (France), Pavia University (Italy), and University of Indonesia (Indonesia) in collaboration with charity associations FAF Auvergne GAIPAR and Normandie-Lorraine. The 2SEES research project is an extension of the Smart Environment Explorer Stick (SEES), which was the first MIMO eETA prototype (Fig. 8) jointly developed by the LIMOS (Blaise Pascal University, France), University of Rouen (France), and University of Indonesia (2011–2014).

The SEES system contains three main components: a global remote server (iSEE), an embedded local server (SEE-phone), and a smart stick (SEE-stick). iSEE is a global server providing web services for VIP such as remote real-time hint and help and remote monitoring (e.g., tracking VIP’s location). The SEE-phone is a commercial smartphone that is used as an embedded local server and provides local services for the SEE-stick, such as itinerary and Internet access to iSEE. Specific functions have been developed to meet VIPs’ requirements (e.g., traffic lights detection). Functions available on SEE-phone, such as voice recognition, will be used to enhance the VIP user-friendly interface. The SEE-phone is always

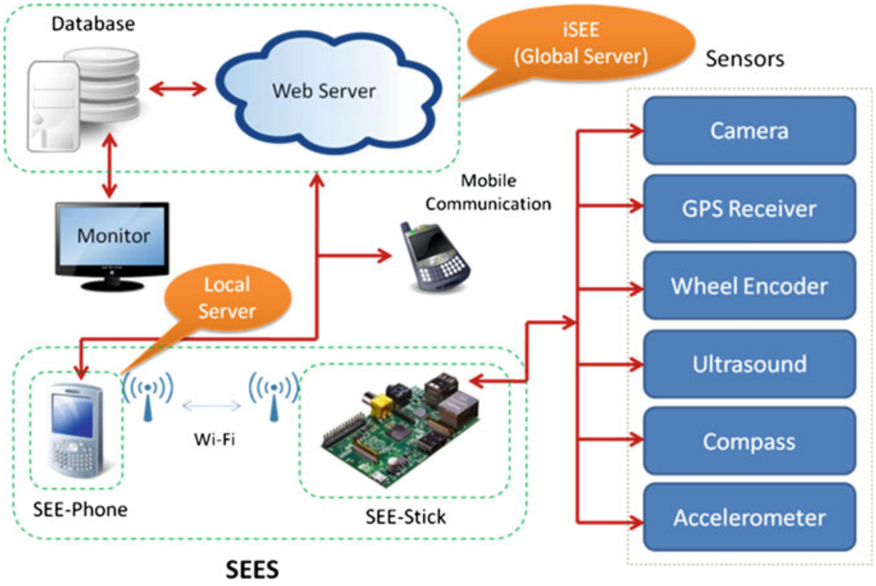


Fig. 8 Architecture of the SEES platform

connected to the SEE-stick through Wi-Fi. The SEE-stick collects data for walking, while SEE-phone is the key device for orientation; indeed, the SEE-phone communicates with the GPS, through the web server accessing to the map database and with other mobile devices.

Using the SEES system, a VIP can know his/her current location. Furthermore, other persons (e.g., friends and family members) can also monitor the VIP's journey remotely. Therefore, the SEES can help VIP to move safely and easily in any place and anywhere (indoors or outdoors).

The main innovation of the SEES is its Internet connection, which enables VIPs to get help and be monitored from anywhere worldwide. Therefore, the SEES is an ubiquitous smart stick [35].

The 2SEES, which will be the successor of the SEES, will have the three following components: the LMSC, a smartphone, and a cloud back end, which functionalities are presented in details in the following sections. The active multi-sensor context-awareness concept is adopted to be implemented in the LMSC to allow a high enough accuracy for obstacle detection and localization while maintaining a high battery lifetime and offering robustness capabilities.

2.2 Functionalities of a MIMO eETA

The functionalities of an eETA should allow VIPs to freely travel and interact with unknown environments. Most of these functionalities can be organized into three categories: obstacle detection, navigation, and environment perception.

2.2.1 Obstacle Detection

In the context of VIP mobility, an obstacle is a difficulty that impedes the movement of a human. Obstacles may have different temporal and spatial properties, and they play different roles in the mobility. Figure 9 presents the objects to be considered as obstacles by 2SEES.

Fixed obstacles (e.g., walls of buildings, curbs, trash cans) keep a constant position on maps over the time. They are space invariants and can be used as spatial cues and landmarks for journey progress monitoring.

Passive mobile obstacles (e.g., table of a café, movable trash cans, signboards, louvers, parked vehicles, open shutters, car mirrors) can change their spatial position but may be considered as static objects with respect to the human motion at a given moment. They provide information on traveled space, social, and urban organization, and might be used as mobility clues; they can confirm the journey progress.

Moving obstacles (bicycles, cars, animals, humans, etc.) usually change their spatial position faster than VIP's motion. They provide/confirm information on traveled space, social and urban organization; they can confirm the journey progress.

The means to detect obstacles depend on both obstacle properties and obstacle role during the travel. To detect fixed or movable obstacles, a combination of several information sources—commonly called "data fusion"—is used. Scalar distance sensors (e.g., ultrasonic transducers, infrared sensors, and laser telemeters) can detect the presence and estimate the distance of obstacles located in front of the VIP, whereas vector or matrix distance sensors (e.g., LIDARs and Time-of-Flight cameras) can be used to detect protruding shapes located in front of the VIP [36]. Images from 2D cameras can also be processed to get an insight on the presence of obstacles. For some objects, it is possible to match a map with very precise localization information provided by a GPS; sometimes, this may be complemented with stereo rig images.

As the user must be able to detect an obstacle before she/he hits it, the detection functionality has a strong real-time constraint: latency. Assuming a detection distance of 2 m by the sensor, a walking speed of 1 m/s, and a reaction time of 1 s, the smart stick should be able to signal the user that there is an obstacle 1 m in front of him/her in less than 1 s to keep a safety distance of roughly one step length. Depending on the detection technique used, it may be more or less easy to guarantee such a latency, or even impossible.

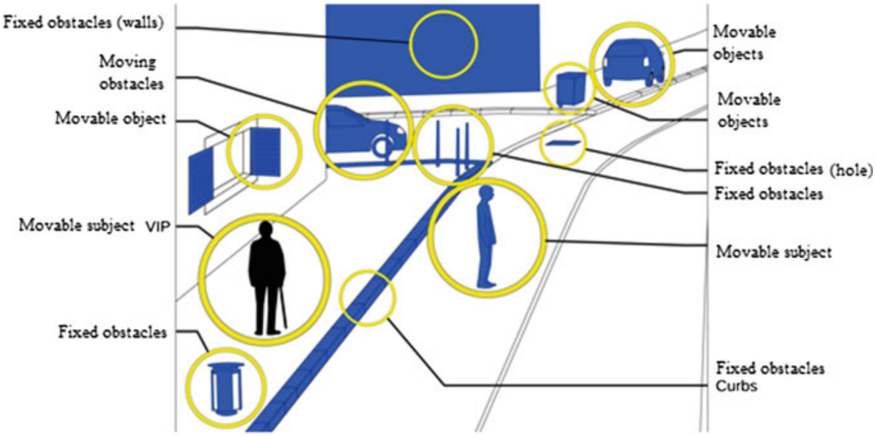


Fig. 9 Obstacles detected by the eETA

Aguerrevere et al. [37] used a sonar range sensing system composed of six ultrasonic transducers to build an approximate representation of the space around the user. The presence of obstacles in six directions around the head of the user was communicated using 3-D space sonification [38].

As described before, the Teletact developed by Farcy et al. [23] is a handheld laser telemeter that can be clipped on a white cane. It has been commercialized and thoroughly tested by users. Teletact can be associated with the “Geotact” that uses a GPS to provide audio navigation assistance in areas where GPS signal is available and precision not critical.

Filipe et al. [39] proposed an obstacle detection system based on the Kinect stereoscopic camera and neural networks. The Kinect camera estimates depth images that contain the distance between the camera and the object along with traditional RGB pictures. By moving the camera in 3D directions, the user scans the environment in front of him. The obtained images are then classified with the help of a neural network in four classes of obstacles: free path, obstacle, upstairs, and downstairs. This method has a very high accuracy: the paper reports approximately 99% of correct classifications—it is also suitable for both indoor and outdoor environments. However, the Kinect requires a rather high power and, more importantly, a high computational capability. Those are two hard constraints in the context of embedded systems. The three previous devices allow a good detection of obstacles and an efficient feedback to the user, but they do not allow indoor navigation.

The detection of moving obstacles implies latency constraints, such that the system end user has time to take actions to avoid them. Usually, sighted subjects detect a moving object (e.g., vehicle, bicycle, horse) using visual pattern recognition, while sightless people mainly detect it from the sound it produces. This difference in used sense explains why any solution using hearing for detection process is not suitable for VIPs.

Intelligent Transportation Systems may share information about the position of vehicles [40]. Because the detection of a vehicle alone is insufficient to predict if a collision is probable, the system must be able to estimate the trajectory of both the user and the vehicle.

Detection of moving obstacles is very challenging with respect to computation time, latency, and accuracy. The accuracy must be very high since on one hand, false negative predicted (i.e., unpredicted) collisions may lead to serious injuries, and on the other hand, given the number of situations of proximity between vehicles and pedestrians without accidents, false positive collision alarms can disturb the user with a lot of useless signaling.

Sound processing can reveal the presence of vehicles and provide information about some types of vehicles (trucks, cars, and motorcycles) [41]. Using the eigenfaces method, it is possible to model the distribution of power in the frequency domain of sounds. In that form, the sound of vehicles can be recognized by comparison to a database of already classified sounds.

Computer vision can also be used for vehicle detection: the smartphone-based obstacle detection system of Tapu et al. [26] is able to detect moving objects and evaluate the risk they present. For that purpose, they extract and track points of interest from the video stream using a multiscale Lucas–Kanade algorithm; the algorithm then makes regional clusters in the images based on the apparent motion in areas. Object features are extracted using Histograms of Oriented Gradients (HOG), which are then used to build Bag-of-Words representations. These representations are finally fed into an SVM classifier so that the system is able to recognize objects.

2.2.2 Mobility: Localization and Tracking

As explained before, VIP mobility consists of two tasks: walking and orientation. Whereas the purpose of the obstacle detection functionality is to support the walking task, the purpose of the mobility and tracking functionality is to allow users to reach their desired destinations, i.e., support the orientation task. This means that the mobility-assistive device should constantly localize the VIP and match his/her current path with a trajectory leading to the target location (Fig. 10).

Localization and Tracking Principles

Localization is the knowledge of the position and the orientation of a body in any terrestrial reference frame. Tracking is the continuous localization of that body.

VIPs' tracking is necessary for at least two reasons:

- The system should provide obstacles information and direction instructions to the user in real time, regularly and upon request;
- The system should provide socio-urban, contextual information in real time (upon request).

The localization function uses kinematic parameters allowing the description of a free body's movement in space (body's tracking): they include its position, its orientation, and its linear and angular velocities. To compute the position and the orientation of a body, it is required to know the three Cartesian coordinates of one of its points and the three orientation angles of the body's own reference frame axes with respect to those of the terrestrial reference frame (R_{Earth}). These six parameters —or degrees of freedom (i.e., three translations and three rotations)—can be directly measured with different sensors.

There are many ways to compute the position and the orientation of a body, but it should be noted that it is a difficult problem, both indoors and outdoors [42]. In outdoors, the availability of absolute positioning systems (e.g., GPS, Galileo, BeiDou) allows easier development of localization technologies than indoors. On the other side, systems designed to work indoors are easier to adapt to outdoor environments.

Furthermore, in order to be widely adopted by VIPs, a smart stick should not rely on a costly, dedicated infrastructure, such as a set of fixed external sensors for tracking the moving object within the volume defined by a 3-D array of sensors. Two solutions remain:

- Usage of so-called "proprioceptive sensors", i.e., embedded sensors whose outputs contain information about various kinematic parameters (e.g., linear and angular velocities and accelerations), allowing the estimation of the absolute position of a moving object in the terrestrial reference frame (R_{Earth}), indoors or outdoors equally;
- Usage of "exteroceptive sensors" measuring environmental parameters, e.g., embedded cameras, LIDARs, and optical encoders. These sensors may or may not have affinities with either indoor or outdoor environments (e.g., satellite signal blocked by roofs, indoors wall structure easier to recognize with a LIDAR).

Localization and Tracking: Sensors and Approaches

Fixed external sensors involved in 3-D motion analysis systems are usually composed of heterogeneous sensors (e.g., video, magnetic) that must be conveniently set in the environment in order to record from different points of view the successive positions of the free body of which movements are studied. As the sensors are fixed in the reference frame, the analysis volume is limited to the intersection of the sensors perception fields, which is convenient for studying numerous human movements, but does not allow the study or the following of large displacements like indoor or outdoor human-free walking.

For that purpose, most approaches use sensors embedded in a portable device. These embedded sensors usually involved for movement data acquisition are wheel encoders, accelerometers, pedometers, gyroscopes, rate gyroscopes, inertial measurement units (IMU) or inertial navigation systems (INS), and cameras.

A wheel encoder can report the distance traveled by one wheel provided that the wheel rolls without slipping on the ground. However, this distance is not representative of the trajectory followed by the contact point between the wheel and the ground, which can be a 3-D curve of any shape. To get the 2-D trajectory of a body or a vehicle rolling on a flat (horizontal or not) surface, two wheel encoders fixed on two separate wheels are necessary.

The ego-centered positions and distances in R_{Earth} of known spatial points which may constitute mobility cues, clues, and landmarks, can be acquired with range sensors, such as ultrasonic transducers, infrared range sensors, laser telemeters, LIDARs, and time-of-flight cameras or a (stereo) camera.

If radio signal is available, it is possible to use it in two ways: triangulation or fingerprinting. If the locations of the radio sources are known, we can have crude information about the position of the receiver by measuring the transmitted powers. Another possibility is to map the fingerprints of the signal intensities of the sources: the localization will then only be the reverse operation, i.e., finding the position from the fingerprints [42].

Outdoors, where it is possible, global positioning systems such as GPS, GLONASS, Galileo or BeiDou, can be used [43].

Wi-Fi fingerprinting [44] is a commonly implemented navigation technique that relies on surrounding Wi-Fi access points to deduce the position of a receiver. This technique allows to create a radio map of the environment and then to compare the Wi-Fi measurements of an object to this map in order to get its position. To improve the robustness of this technique with regard to the difference of characteristics between the devices used during cartography from those used during localization, advanced error modeling methods are required. This method has the advantages of constant precision with respect to time (like the GPS) and somewhat low computational requirements. However, it has at least two drawbacks: it needs a precise radio mapping of the environment and a good Wi-Fi infrastructure. It can be applied both indoors and outdoors.

Li et al. [45] proposed an indoor localization system that exploits the LED lighting infrastructure to transmit information, using their ability to quickly switch on and off. Every lamp of the lighting infrastructure emits a different signal containing its position, which is detected by a camera carried by the user. A smartphone camera can be used for this purpose. The camera outputs both the position of the lamps it sees and their signal strength (i.e., how much light is received). From this information, an algorithm is able to estimate the position of the camera, and thus that of the user. The LED bulbs use binary frequency shift keying (BFSK) modulation to encode their data; as they all share the same medium (visible light), collision avoidance techniques are implemented. Channel hopping is used: basic time periods are divided into slots, and every bulb randomly chooses one of these slots. As long as the number of slots is high enough with respect to the number of bulbs, collisions have a statistically negligible importance. This method is very accurate (about 40 cm accuracy is reported) and makes use of a necessary infrastructure (lighting) instead of adding another one. This infrastructure still has non-trivial constraints: lighting must be done by LED bulbs that must be paired to special circuits to generate the broadcast signals.

Riehle et al. [46] proposed a VIP indoor tracking system based on the magnetic signature of a building. Modern buildings, due to their steel, reinforced concrete structure, and power systems, generate distortions in the magnetic field. These distortions present enough temporal stability and space variability to be used in location systems. However, most of these solutions rely on accurate mapping of the magnetic field, which takes time and effort. The system developed by Riehle et al. [46] surveys the building magnetic signatures (a sighted “leader”) only on routes of interest, and signals points of interest along these routes. The blind traveler following these routes is warned by a sound if she or he diverges from it. This system reduces the need of professional surveying and drastically reduces the cost. An implementation was realized using a smartphone and two IMU chips, each containing three-axis gyroscopes, accelerometers, and magnetometers. The strong points of this solution are the elimination of the need of a specific infrastructure and of precise building surveying, as well as the low cost of the solution. However, it still requires upstream work of a leader and provides only a restricted, point-to-point navigation solution: if the user deviates from the pre-existing paths, his location will not be determined. Suitable conditions for this system might also be restrictive: not all buildings possess a steel structure and electrical power systems (e.g., ancient buildings).

Another class of approaches uses accelerometer, an inertial sensor designed for measuring one or several components of the linear acceleration of a free body. As a first approach, let us consider a one-axis accelerometer made with a box containing a sensitive cell composed of a small mass fixed to a spring and located at point M. The mass (m) of M and the stiffness (k) of the spring are known from construction. A reference frame R_{A} (origin A) is linked to the box and the axis (x) defined by vector $\boldsymbol{AM}$ represents the measurement direction of the accelerometer (Fig. 11a).

According to Newton’s Second Law, when the box is submitted to an acceleration along its measurement direction (x), the mass exerts on the spring a force $\boldsymbol{F}$ (Fig. 11b) that is directly proportional to the submitted acceleration $\boldsymbol{a}(M/R_{\mathrm{A}})$, which is then computed as follows Eq. (2):

$$\vec{F} = m\vec{a}(M/R_A) \quad \text{thus: } \vec{a}(M/R_A) = \frac{\vec{F}}{m}. \tag{2}$$

Accounting to the miniaturization of the sensitive cell components, the spring length and the mass movements within R_{A} are assumed to be negligible. These

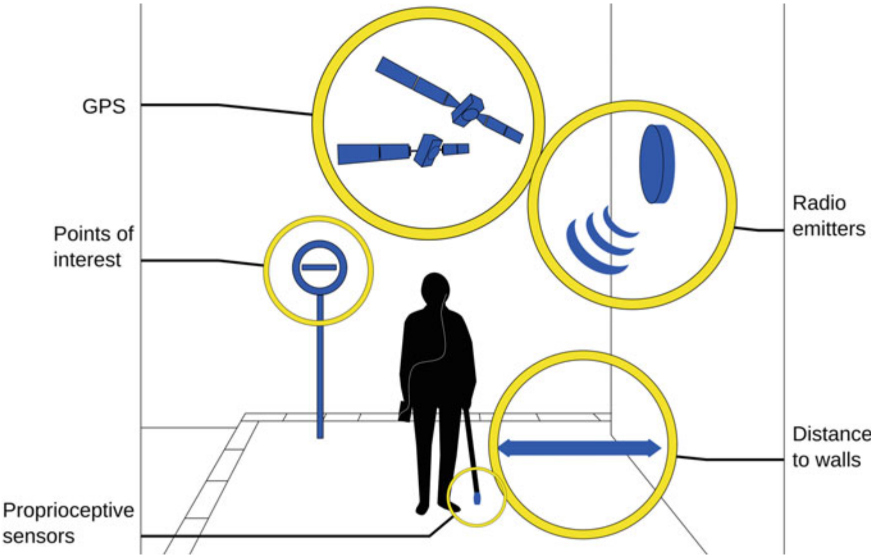


Fig. 10 Overview of the localization technologies for the eETA

assumptions lead to consider that both points M and A are superimposed and thus the acceleration measured by the accelerometer is that of the origin A of R_A.

In the reality of a free body's movement, it is not possible to know a priori in which direction of the terrestrial reference frame (R_{Earth}) it will move. It is also quite impossible to precisely fix an accelerometer along one axis of the body (e.g., shaft axis of a white cane): it is thus relevant to use a 3-D accelerometer and to fix it in any position on a known point of the body.

The use of a single 3-D accelerometer only enables to study the translations of a free body moving on a flat horizontal or inclined floor. Moreover, these limited conditions do not allow computing the distance traveled by the free body along a straight line on a horizontal floor with a convenient precision because of the integration drift of the acceleration and of the unevenness of the floor [47–49]. They also do not allow rebuilding the trajectory followed by the free body during any displacement. Indeed, if the body is moving with both translations and rotations in R_{Earth}, the acceleration measured by the accelerometer is the driving acceleration, which is the vectorial sum of several terms (e.g., tangential and centripetal components) that cannot be computed without knowing the instantaneous angular velocity of R_A with respect to R_{Earth}. As a consequence, to get the other kinematic parameters of a free body's displacement, it is necessary to quantify its rotations, which can only be done with the help of other inertial sensors, like gyroscopes and rate gyroscopes.

The name "gyroscope" was given by Léon Foucault to the device he designed in 1852 for the first inertial experiments that exhibited the Earth's rotation. Indeed, this device allowed viewing the rotation of its box with respect to a fixed direction in

R_{Earth}. Originally, this device contained a rotor—or spinning top—rotating at such a high speed that its rotation axis kept a fixed direction with respect to R_{Earth}, whatever the movement of its box or of the body on which it is fixed. This phenomenon derives from the principle of angular momentum conservation [50–52], which requires that at the initial instant the gyroscope rotates around the spinning axis, and that the vectorial sum of the moments of external forces applied on its center of mass G is null.

The behavior of gyroscopes is the reason of their use as navigation instruments on ships (1865: gyrocompass), and then on planes (1914: artificial horizon), for determining a fixed direction with respect to R_{Earth}, which is assumed to be Galilean. Gyroscopes embedded in these instruments generally have two axes, and the spinning axis can be oriented either horizontally (gyrocompass) or vertically (artificial horizon): in the first case, the gyroscope gives a measure of the free body's orientation with respect to the geographic North (yaw angle), whereas in the second case it indicates its roll and pitch angles.

As gyroscopes allow to measure rotation angles of a free body, they were logically used for building the first instruments designed for measuring angular velocities: rate gyroscopes. A rate gyroscope is a one-axis gyroscope that measures the component of the instantaneous rotation velocity of its box along yaw, roll, or pitch axis. Thanks to the development and miniaturization electronic components, new types of rate gyroscopes without spinning top—simpler, more compact, more reliable, and less expensive—have appeared in the last decades: laser, whirlpool, or tuning fork rate gyroscopes [52]. The latter ones get the rotation velocity from the measurement of the Coriolis's inertial force acting on a vibrating elastic blade. The small dimensions of these devices make them particularly convenient to be embedded in mini Inertial Measurement Units (IMU).

An IMU (and INS, inertial navigation system) is a composite sensor integrating three accelerometers, which measure the components of the linear acceleration of the free body along the three orthogonal axes of its own reference frame (R_{A}), and three rate gyroscopes, which measure the components of the instantaneous rotation velocity of the free body around the three axes of R_{A}. Some IMU/INS also includes magnetometers that measure the three components of their orientation with respect to the earth magnetic field. Finally, an integrated processor directly gives the three orientation angles (α, β, γ) of the IMU/INS reference frame (R_{A}) with respect to the axes of R_{Earth}.

Inertial sensors work along mechanical principles that allow them to measure the driving acceleration (accelerometers), the orientation (gyroscopes), or the instantaneous angular velocity (rate gyroscopes) of the free body on which they are fixed. The improvements and the miniaturization of electronics components during the last decades have allowed to integrate these devices within compact and light measurement systems that can be now used in many applications where their low mass and low bulk are criteria of main importance [47, 53–63].

When compared to 3-D movement analysis systems based on video, inertial sensors are "blind" as they do not take information in the nearby environment. Indeed, their name comes from their ability to measure some kinematic values of their own movement, assuming that they move within a Galilean—or “inertial”—reference frame. From these measurements and the knowledge of the movement initial conditions, it is possible to compute their three orientation angles and the three components of their linear velocity in R_{Earth}. It is also possible to compute their trajectory provided their absolute position and orientation are periodically updated during the movement. For these reasons, they have been used for a long time in sea and air navigation for computing the orientation and the direction followed by ships and aircraft without earth benchmarks or when visibility is low or null (e.g., fog, cloud, night).

Moreover, inertial sensors have the following advantages:

- They can be directly fixed on the body (e.g., vehicle, boat, air plane, human) of which movement is studied (“strap-down” systems);
- They are not submitted to the use limits of 3-D movement analysis systems (e.g., restricted analysis volume, temporally hidden, or lost markers);
- Some kinematic values of the body’s movement can be computed in real time by an embedded processor, which reduces the processing time;
- Their cost is relatively low with respect to 3-D movement analysis systems composed of several high-speed video cameras, for instance.

Conversely, the use of inertial sensors requires some caution because the kinematic parameters (i.e., linear velocities, orientations, and positions) computed from their measurements are subjected to different error sources like integration drift [47, 48, 57, 60, 62]. It is thus necessary to regularly measure their position and their orientation within the Earth magnetic field using magnetometers. But, in turn, magnetic sensors have a drawback: they are sensitive to the environment magnetic disturbances due to the proximity of magnetic sources or metallic objects [63].

The reasons for using inertial sensors for VIPs’ navigation can be diverse, as well as the kinematic parameters to be computed from these measurements.

Naqvib et al. [64] developed a pedometer based on the accelerometer embedded in most smartphones. The user placed the smartphone at the waist level, typically in a pocket, and a program used the accelerometer signal for detecting and counting the user’s steps. The steps count is then multiplied by the average step length to compute the distance traveled by the user, which is a very important information in a navigation system. This system is interesting given the low material constraints (a smartphone in a pocket) and the use of an accelerometer; furthermore, it can equally be used indoors or outdoors. However, it needs a good estimate of the average step length, and it might be affected by an irregular gait. It thus quickly accumulates error so that it cannot be confidently used alone for tracking the displacement of a VIP.

Zheng et al. [65] used inertial sensors in a shoe-mounted configuration in an indoor pedestrian navigation system. This system uses zero-velocity updates to correct the drift due to time integration of inertial sensors data. It also uses an extended Kalman filter to estimate and to correct the error parameters of the sensors. The filter uses the stance phase—when the foot is lying on the ground—to get the

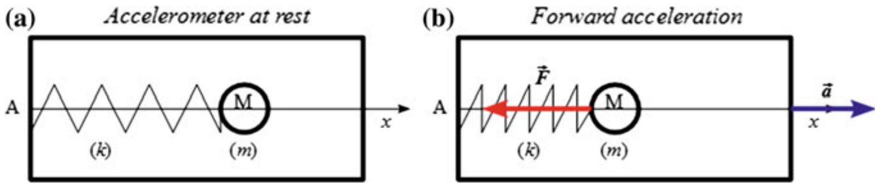


Fig. 11 Operating principle of a one-axis accelerometer

error parameters of the IMU, which are then used to correct the computed position and heading. This technique provides the self-reliance of inertial sensors while allowing a good accuracy that is less than 1% of the total traveled distance. However, the foot-mounted position of the IMU can limit the usability of this technique for VIPs' displacements.

2.2.3 Collaborative Elaboration of the Journey Path

Guiding the user to his or her destination requires a path to be computed. The previously seen methods for localization and tracking will then be applied to know the position of the user with respect to this path and guide her or him accordingly. The quality of the paths users will have to follow is very important for them. In order to globally enhance this quality, to build computation rules of a good path, and to help the user to choose the path that suits him or her, some form of communication between the user and the path computation system is required.

The goal of the path computation system is to find the shortest and most secured path that should fulfill several criteria:

- Dangers should be avoided as much as possible;
- The clutter level of the path (density of obstacles on the path);
- The presence of assistive devices (e.g., tactile surface paving) or guiding elements along the path (e.g., straight walls, curbs).

The route should also take into account the precision of localization sensors: if information relative to their performance or to the required processing power along the path is known, it should be used in the optimization process. In particular, paths where the system is likely to lose track of its localization, as well as those without wireless network coverage, should be avoided.

The collaboration will take place at two levels:

- Between the user and the system in general;
- Between the local server (e.g., smartphone) and the cloud back end.

Short- and long-term components are included in both contexts. In the first one, the short-term collaboration is the proposition/revision/acceptance mechanism: that way, users can reject paths that they know they will not like, and it increases the confidence they have in the results given by the smart stick. On a longer term, the system is able to learn the user's specific habits and tastes to directly propose higher quality solutions. Regarding collaboration between the local server (smartphone) and the global cloud back end, the short-term component is the communication of map, traffic, accidents, and other contextual information related to the traveled locations. The long-term component is the compilation of individual preferences from local servers to infer global preferences of the users.

Man–Machine Collaboration

During trips, communication between the user and the system is essential for the latter to guide the former. These communications can be done through vocal synthesis on one hand, and vocal recognition on the other hand, as it avoids the cost and complexity of a keyboard and Braille display.

At start the user must inform the system about his destination and let the system localize his or her initial point. During the displacement, the system provides directives that are important for reaching the target place at strategic mobility spatio-temporal points (e.g., changing of direction or drift warnings or confirmation of the progress). Indeed, the VIP's feeling of safety requires that the system informs him or her regularly, but sparingly, about the journey progress.

Essentially, four constraints apply on the guidance instructions:

- They must be steadily output;
- They must be clear (messages should not contain any explicit or implicit ambiguity).
- Instructions will be generated in terms the VIP has learnt in mobility classes (terms and units);
- System must inform the VIP when she or he has reached the target.

Gaunet and Briffault [66] have worked on the design of rules suited to guidance of visually impaired and blind people in outdoor environments. They have analyzed route descriptions given by blind pedestrians to infer guidance rules. They found that a limited set of functions can be used to guide blind people, for instance, describing the location and orientation of the user, describing an intersection, crosswalks, etc. However, this work should be extended with locomotion teachers.

Man–Man Collaboration

In some circumstances, navigation algorithms can be too limited to ensure the safety and satisfaction of a VIP. It can happen because the estimated position and orientation of the smart cane has drifted and reached large-scale errors in guiding. It can also happen because the system detects by itself that it cannot ensure sufficient guiding accuracy in an area that will be traversed, because of the lack of meaningful cues to extract from the environment, or simply because the system battery is discharged. Therefore, the smart cane might not work correctly, or be inefficient for a specific task. In these cases, direct assistance of a human operator should be provided.

The video feed from the smart cane's camera must thus be transmitted to the operator, who will guide the user according to what she or he sees—as if the operator were giving directions while being near the user. With good enough image quality and latency, an operator should be able to give correct instructions. Besides, it could be reassuring for users to be guided by a human being instead of by a machine. Furthermore, knowing that it is possible to talk with someone could help breaking potential loneliness or anguish.

People giving directions can be family members, friends, volunteers, or professionals. Because being remotely guided means that the VIP must have a very high confidence in the guide, friends, and family should be solicited first; then, volunteers, and, finally, professionals. To build up trust, successful associations between a user and a guide should be maintained as much as possible. The tool used by operators would preferably be a mobile application displaying a map together with the video. That way, volunteers could give assistance in various situations, without being forced to dedicate themselves to this task.

2.2.4 Environment Perception

The eETA should provide information on the surrounding environment so that it will help VIPs to enhance their ability to perceive it (Fig. 12). Going out for VIP should become a new social and leisure activity.

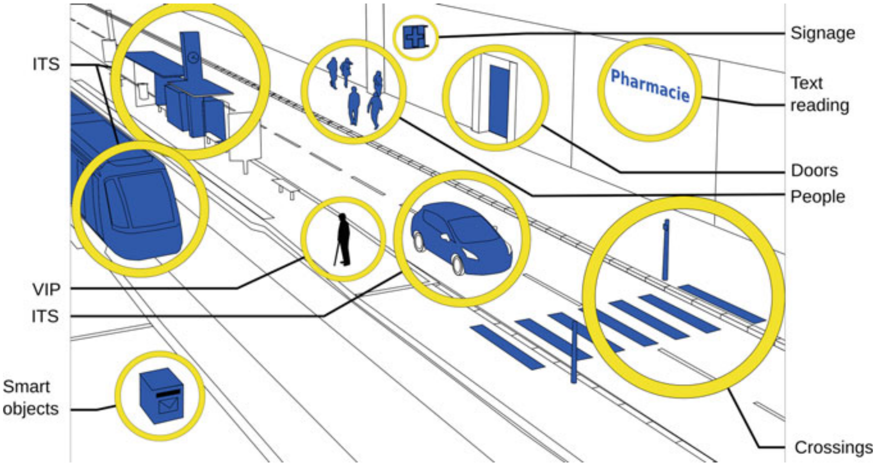


Fig. 12 Overview of the environmental perception functionalities of the eETA

Street Crossing and Assistance

Street crossing is one of the major problems for VIPs for several reasons: estimation of vehicles' (cars, bicycles, etc.) motion with respect to their own motion and fast real-time ego-perception capabilities; localization of pedestrian crossing; and mobility cues changes. There is a possibility that a driver does not see a person crossing and does not stop, even if the traffic light is red. Sighted people can spot such a vehicle from a distance; however, it is difficult or even impossible for VIPs to do the same. Moreover, sighted people can estimate the time before a vehicle arrives at the location they want to cross, and decide whether to cross or not based on this information; VIP can hardly do it. Therefore, it is much more dangerous for the latter to cross roads lonely, and even if there is no danger, it is likely that they will not feel at ease crossing. In order to get enough confidence to cross a road, a VIP may spend a lot of time analyzing the traffic and waiting for the absence of vehicles. In some areas, with slow but continuous traffic, it even may be impossible for VIP to cross [67]. Crossing a road may induce several problems:

- Pedestrian crossings may be difficult to locate, especially when there are no tactile guidance paths. Therefore, VIPs use environmental clues, like the noise of streets intersection. Indeed, such noise is specific, learnt during the mobility classes and recognized by VIPs;
- Crossing a street outside pedestrian crossings is extremely dangerous for VIPs. Indeed, they can hardly find suitable locations for crossing: for instance, how may a blind person know that the road is turning 15 m after the place where she or he is crossing? Similarly, it may be difficult or impossible to know the speed limit on a road;
- Crossing a road may induce a loss of orientation. In some configurations, the physical properties of buildings surfaces change before and after crossing. This is an extremely confusing situation, as many VIPs with specific ear air pressure capability (named "mass perception") use walls as a cue to follow;
- It is also possible that the direction of the VIP changes while crossing a road, especially in complex configurations (e.g., with an island in the middle).

Hence, crossing assistance should be provided in three ways:

- Localization of pedestrian crossings;
- Identification of the best moment to cross safely;
- Helping the user to keep a straight direction.

Systems to help VIP in these three aspects have been developed. Wang and Tian [68] used an RGBD camera to detect both stairs and pedestrian crosswalks. They use RGB images to indiscriminately recognize them (as they both appear as horizontal lines), and then categorize them as up-going stairs, down-going stairs, or crosswalk according to the depth information of the camera, with the help of an SVM classifier.

Ivanchenko et al. [69] developed a system that can detect "zebra" pedestrian crossings and another one that helps the user keeping the right direction along two-stripe crosswalks [70]. Both functionalities run on a smartphone, processing images from the onboard camera. Zebra crosswalk detection uses multiple cues to recognize the parallel bands of crosswalks with a good accuracy; it signals users with an audio tone when they are aligned with the crosswalk. The two-line crosswalk alignment system makes use of the smartphone accelerometer to detect the horizon and only select the lines on the ground (i.e., below the horizon), and then detects the presence of strong parallel lines. When a single line is detected, the smartphone emits a low pitch noise, and when two lines are detected, the smartphone emits a high pitch noise: this way, the user can find the direction of a crosswalk.

Specific Signage Detection

Signage is a prime example of information embedded in the environment. Indeed, the purpose of signage is to communicate information to a specific population. Therefore, it can be of high utility to communicate the contents of signage elements to VIPs who cannot or hardly see them.

Which particular signage must be detected and described should be selected on the basis of the context at that time. This context has several facets: it includes what is generally useful for users, which can be statically defined or statistically inferred. It also includes personal preferences of users, which they can input into the system, or which can once again be statistically inferred. More importantly maybe, it includes the current goal and desires of the users (i.e., what they are looking for), which can also be input in the system. Specific signage could be elaborated in order to provide data useful for VIPs' journey progress, which may be already existing signage or objects (useful for sighted), but also new objects, which are helpful to VIPs only.

Wang and Tian [71] worked on a framework to recognize signage and doors. To spare computation time, they first computed a saliency map to find areas having the highest probabilities to feature the searched elements. These areas are then scanned with a sliding window, in which a bipartite graph matching algorithm is used to compare the content of the window to the signage of interest. In their experiments, these authors have tested their software to detect open/close door elevator buttons, men/women/disabled bathroom pictograms, and direction arrows.

Detection of Specific Objects in the Vicinity of VIPs

The identification or recognition of some objects can be useful; the information can either directly be communicated to the user, or be used in the system to compute or refine information. Indoors, doors are very important for users, as they are the main way of circulating in a building. Other objects (e.g., furniture, appliances, electronic devices) can also be of interest, depending on what the VIP wants to do. Detection of any object can be interesting: a broader detection range implies a broader range of situations that can be attended; hence, more freedom. Outdoors, apart from signage and obstacles, elements of street furniture (e.g., benches, post boxes, bus or tramway stations, bins) can be useful. Both indoors and outdoors, in an unknown context—where an assistance device is the most useful—it is likely that the main goal is the navigation to a specific location in the building (e.g., airport, mall, public, or private buildings).

For indirect use (i.e., when the information is not communicated to the user but used in an internal process) several types of objects are interesting. First, all objects referenced on the map can be used to compute or correct the localization, acting as references. This usage is strongly dependent on the richness of the map. All objects cannot be referenced on a map: most of them are very likely to move or disappear. Only fixed objects should be considered; indoors, this should particularly be the case with doors, and outdoors, the fixed street furniture. Second, the function of the location where the VIP is can be inferred from the presence of objects in a room: for instance, is it an office, a bathroom, a living room…

Several sensing mechanisms may allow detection and recognition of objects around the user. Pattern recognition is the main method used by sighted people to recognize objects. However, this approach is scientifically difficult to reproduce and of high computational complexity. Another method is to use wireless network messages to identify objects. Without a heavy added infrastructure (i.e., putting an identification chip on every object), it is only possible for “smart” objects, of which number should grow steadily in the next coming years [72]. The previous paragraph briefly exposed how objects referenced on the map can give an insight on the position and orientation of the smart stick when they are detected. The opposite is also possible, that is, using map data about locations to detect objects. In particular, this can be used in information fusion, to get more confidence in the results of image or radio detection.

Tian et al. [73] have developed a method implemented in a program that can recognize doors. For that purpose, they used the following model: doors are composed of four corners and four lines of which two are parallel, and they are recessing inside walls (in opposition to furniture that is protruding from walls). As it is unlikely that a VIP is able to fully frame a door with a camera, since he or she is not able to see it, Tian et al. took the partial visibility of doors into account.

Yi et al. [74] proposed to use both a network of fixed cameras distributed in the rooms of a home and a camera held by the user. The user informs by speech the system that she or he is looking for a specific item, whose appearance has previously been learned. Then, all fixed cameras search for that item, and, when one finds it, its location (e.g., “in the kitchen”) is reported. The user can thereafter go there to search more precisely the object with the handheld camera.

Transports Schedule Communication

Even for sighted people, using public transportation can sometimes be difficult; so, for VIPs, it is often nearly impossible. To be able to use a transport, there are several steps:

- Users must locate a bus, tramway, or subway station;
- They must reach the platform;
- They must know which stations are included in the line;
- They must know the timetable of the transport;
- They must have a travel ticket (in most countries);
- They must be physically able to board the vehicle.

The first and second steps are mainly managed by the localization functionality. The complexity of the second step greatly varies, both in nature and in magnitude: discriminating the two sides of a tramway station may be difficult—in particular if localization relies on GPS—and guiding a blind user in the corridors of a convoluted multi-floor subway hub may also be challenging. The fourth step has two levels: the first one is the knowledge of the time until the next transport vehicle arrives in the station; this information is often provided to travelers on a screen, and is thus not accessible to most VIPs. The second level is the knowledge of the whole timetable, which is useful in planning phases. The order of these steps is not fixed and depends on the context: someone may want to know the timetables and location to make plans before traveling, but someone else may decide things on spot.

As said before, the two first steps are mostly within the purview of the navigation functionality. The third and fourth steps are about communication of line information to the user. Essentially, two ways are available for the smart cane to access transport line information: by the Internet or directly from the station. In the second case, two methods exist: if possible, the smart stick will connect wirelessly to the station and request the timetable. Hopefully, in the current context of development of intelligent transport systems, it is likely that both vehicles and stations will be more and more capable. In particular, it could mean that the stations would provide wireless local services to users, through IEEE 802.15.4 or Bluetooth Low Energy for instance. If wireless connection to the station were not possible, the smart stick could use image processing to extract information from the visual displays in the station. This solution is much more complex, and would certainly require other information to be efficient. A first problem would be to localize the display panel; for that, a model of the station could be used together with a precise localization of the stick and of the station, to help the user pointing the camera toward the panel. In a second time, an a priori model of the timetable or line description displays could be used to efficiently extract data from them.

Text Reading

Textual information is usually ubiquitous as it is displayed everywhere in modern environments, be it on signage, on informative panels (e.g., in restaurants), or on objects. More often than not, it is not possible to obtain this information through another mean than vision. And even when the information is also written in braille, or can be automatically read by a device, VIPs do not necessarily have the knowledge that information is available, and they need to move their camera close to the text to read it. Functionality designed to replace the user's ability to read texts would thus be welcomed.

The only sensor able to retrieve all textual information is a camera. Fortunately, a lot of work has been done in this area, since it is useful in many fields (e.g., document scanning, license plate recognition) [75]. However, there are additional difficulties in the case of assistance tools for VIPs:

- The environment is uncontrolled (i.e., the text can be present on any support or background);
- The position and orientation of the camera are uncontrolled (i.e., the user does not know where to orient the camera and will probably not keep a steady orientation);
- The structure of texts is uncontrolled (i.e., how to know if blocks of text are related, and how to communicate efficiently the contents of several related or independent blocks of text).

Yi and Tian [76] have developed a novel text recognition method in the context of assistance to VIP and blind people. This method works in two phases: first, text regions in the pictures are detected by segmenting images into regions with unique colors, and then searching for horizontal alignment inside the regions—as it appears that most texts are aligned and have constant colors. The second phase is the recognition of characters in the text. To do it, Yi and Tian use the Harris, MSER, dense, and random key point extractors and histograms of oriented gradients (HOG) to create feature vectors; these vectors are then aggregated using a Bag-of-Words (BOW) model and a Gaussian Mixture Model (GMM) to create character descriptors. The system has been implemented as a smartphone application and was able to recognize texts in testing datasets with a better accuracy rate than most other solutions.

Locational Context Information

VIPs would greatly benefit from general, contextual knowledge about the places they visit. This contextual knowledge may be of several natures:

- The domain of the location: public or private;
- The nature/function of the location: public square, kitchen, corridor, subway station, etc.;
- More general knowledge about the location: history, trivia.

Such knowledge would have several benefits. First, it gives information to the users about what they can expect around them, limiting surprises; in some cases, it can reduce the probability of dangers (e.g., walking on a road without curbs). Second, it provides spatial feedback, indicating to VIPs whether they are on the right path, by communicating mobility cues that are specific to locations and that VIPs can recognize. Third, it may help people remembering locations by attaching a meaning to them, which is normally an easier and more efficient memory process than learning by heart.

Locational context information can be stored in various geographic databases or inferred from other data. These two methods—storing locational information or inferring it—have different complexities. The first method is simpler in the front end—accessing a database—than in the back end—the database either needs to be filled by hand or information extracted from public, open data sources that can reasonably be assumed to be trustworthy. The complexity of the second method mainly lies in the front end. Indeed, in that case, the working principle is akin to that of an expert system: rules are defined, evidences are collected from sensor data and known information, and, using these, an inference engine can find new information —in our case, about a location. The rules would be of the form "If there is a fridge nearby, then the room is a kitchen with a confidence of 60%" [77]. The choice between methods is not binary, and the smart cane could take advantage of both, as they have different qualities and application domains. With sufficient information, it should be possible for the system to try to guess the function of a location and communicate to a user.

Human Detection

Because humans are social beings, interactions, and communication with other individuals are of prime importance. People tend to change their behavior in the presence of others. Therefore, knowledge about the number and general attitude of people can be beneficial for VIPs.

Furthermore, communication between people comprises not only words, but also nonverbal cues, like facial expressions, body posture, gestures, and gaze. Unfortunately, for VIPs, a very significant part of these nonverbal cues are normally acquired through vision. In a focused context (e.g., a conversation), it would be useful for the smart cane to communicate to its user some of the visual nonverbal cues of the interlocutor.

Another problem to be addressed is the identification of specific characteristics of people. In particular, some details may allow recognizing people whose task is to help others. It is common to seek assistance in unfamiliar locations; for blind and VIP, it is twice as important, since they have much more difficulties adapting to unfamiliar settings. As, usually, such people can only be discriminated from the others from visual cues (e.g., badge or uniform), VIPs often cannot independently locate them.

Image processing is the method with the highest potential in this domain. It has been extensively used for facial expression recognition [78] and for gaze tracking [79]. It has also been used for clothing recognition [80]. Other sensors can be used in the required estimations: a microphone and signal processing can give insights on the number of people around the user [81]; a depth camera system can provide meaningful information about gestures and body posture [82].

2.3 System Constraints

System constraints globally apply to all the smart stick functionalities, from hardware to software.

2.3.1 Usability

The purpose of the smart cane is to allow VIP to move around like sighted people do. The cane is, essentially, a tool that provides freedom (including safety) and warns others about the fragility of its owner. Hence, the eETA should not make its user feel constrained, which would cancel its benefits. This means that this device should be light enough, have a long lifetime, and be dependable.

The physical efforts of the user should be limited to the minimum:

- Carried weight should be minimal;
- Required motions should be limited;
- Carried weight should be placed where it stresses the least (e.g., close to the center of mass of the user).

The eETA lifetime should be long enough to allow continuous use in difficult contexts. The device should be able to run for at least 12 h, approximately a working day, without being charged. In order to reach such a long running lifetime, energetically costly components and operations should only be switched xxxON when needed (sustainable design).

Other characteristics linked to cane management (e.g., pliability, maintenance) should be established with end users.

2.3.2 Dependability

Smart cane users will only trust it, if it is dependable. Dependability comprises six different attributes [83]:

- Availability;
- Reliability;
- Safety;
- Confidentiality;
- Integrity; and
- Maintainability.

Availability designates the readiness for correct service of the system. It means that in spite of the environmental difficulties, the cane must be able to start up and provide reliable obstacle detection functionality. More generally, it should be able to run a set of tests, to determine how much functionality can be provided to the user with acceptable confidence, and to detect faulty components in the system.

In our case, the system has three physical components (smart cane front end, smartphone, cloud back end), which should be able to start up, initialize, and be ready for use quickly when the user wants to use the eETA. Due to the complexity of this device, it is likely that running in a fully functional mode will not be possible all the time; for instance, the system may be used in locations without cellular network coverage. In these places, the smart cane will not be able to connect to the cloud back end, to download maps or to stream video to a remote operator. Basically, the only possible functionality of the smart cane will be obstacle detection.

Reliability means continuity of correct service. As well as self-testing at startup time, the system should be able to adapt to new conditions especially if they worsen. For instance, it should be able to handle transitions from areas covered by GPS to areas without coverage. Essentially, the functionalities should be able to provide correct accuracies as far as allowed by the context. In particular, the estimated localization of the user should remain correct and should not gradually drift over time.

Ensuring the *safety* of the user is a very tricky task. Indeed, the range of contexts that can be encountered is not limited; and any of these contexts can present threats. Even for able-bodied people, it is not possible to provide complete safety in a controlled or uncontrolled environment. But dangers induced by the device should be avoided at all costs. These dangers have roots in three sources. First, the usage of a smart cane can lead—in an ideal world—to trips to more unfamiliar locations, inducing new dangers (e.g., traveling in a foreign country where driving rules are different). Second, it can increase the frequency of trips outside of safe zones, which mechanically increases the probability of having an accident. Third, if the smart stick appears to work well and reliably, the user may rely on the device to an important extent. In such a case, it is possible that the user lessens its caution level —putting him in danger in cases where the cane does not detect the hazard. In order to increase safety, these three sources of dangers should be mitigated, while giving the smart cane capacities to avoid the "normal" hazardous situations.

Confidentiality is not a trivial problem. On one hand, the smart cane is working with personal information (user profile): trips of the users, images of their environments, preferences, etc.; on the other hand, by its very nature, the smart cane is connected to external networks, allowing attacks. Furthermore, there are several gates to the system, since it spans over several subsystems, both physically and logically. Information may leak in the cloud back end, from the smartphone, or in the network between them. Unauthorized disclosures could also take place when the device communicates with smart objects or intelligent transport systems (ITS).

Both physical and software *integrity* are necessary, at a high level: if the smart cane breaks easily (as an object), the user will not be able to use it anymore and will probably regard it as useless. Likewise, if the software blocks durably, the assistive functions cannot be recovered by rebooting.

The last attribute that makes up dependability is *maintainability*. The smart cane system should be able to keep in a good state without direct human intervention for as long as possible. Outside hardware modifications, it should be possible to perform all maintenance operations remotely and seamlessly, since it cannot be expected that all VIPs can work with software.

2.4 Sustainable Design and Development

Objectives of such design are twofold:

(a) human: a design that matches

  - user expectations (weight, maneuverability, adaptation to different assistance levels (environment, age), wearability, aesthetics);
  - required level of confidentially (see above).

(b) technical: minimize the energy consumption, use of low-cost components, activation/deactivation of components, seamless update of software (ubiquity).

3 Local MIMO Smart Cane Prototype: Software and Hardware

3.1 Hardware Architecture

The Local MIMO Smart Cane (LMSC), whose features have been presented earlier in this section, is a connected embedded multi-sensor system (or embedded sensor node or sensor node or node). These nodes are used in Embedded Wireless Sensor Networks (EWSNs), Internet of Things (IoT), and Cyber Physical Systems (CPS) research domains. A node is connected to sensors that collect information about its environment and it communicates with neighbor nodes or with a sink node over wireless network. Sensor nodes must meet many constraints: they must be low cost, consume little energy (e.g., more than 8 hours of battery life for the LMSC), and be dependable and reconfigurable.

Currently, most of existing nodes are connected to few sensors and are built on single-core architecture, which is made up of four basic units (Fig. 13): a sensing unit, a processing unit, a transceiver unit, and a power unit [84].

The sensing unit collects environmental analog signal and converts it to digital data. The processing unit executes the operating system and the application. The transceiver unit connects the node to the wireless network. The power unit supplies power to the other units and its features define the lifetime of the node.

Single-core architectures will, however, soon be outdated. Indeed, since their processing capabilities are exceeded [85, 86], emerging WSN applications use more and more sensors, including multimedia sensor like a camera. Nodes have increasingly heterogeneous data to process and to transmit in real time.

The LMSC belongs to this new generation of WSN applications. It embeds many heterogeneous sensors for giving information about their environment to VIPs: obstacles, Points Of Interest (POI), direction to move, etc. It must store, process, and fuse in real time all the data originating from its heterogeneous sensors. It must also be fault tolerant.

In order to satisfy the needs of emerging WSN applications, researchers have recently begun to work on multi-core architectures for sensor nodes. Notice that if the number of cores present in the processor is high, we speak of many-core architecture. If the cores are physically separated, we speak of multi-CPU architecture.

A multi-core architecture (Fig. 14) is very similar to the single-core architecture. If we look at the multi-core architecture introduced by Munir et al. [87], we can see that the main difference is the use of a multi-core processor instead of a single-core processor.

The main interest of multi-core architecture is that multi-core nodes can run applications requiring a high computational power while achieving energy savings [88–90]. Some of their most interesting new characteristics are the following:

- As a multi-core node has more computing power, it can reduce transmissions by processing locally some parts of the sensed data;
- Several low-powered cores working in parallel consume less energy than an equivalent single-core [91];
- It is possible to completely switch off a core when it is not used to minimize energy consumption;
- A multi-core sensor node is more robust than a single-core sensor node: if one of the cores is broken down, the others can continue to run in degraded mode.

For our LMSC prototype we have chosen to use an asymmetric ON/OFF multi-CPU architecture (Fig. 15).

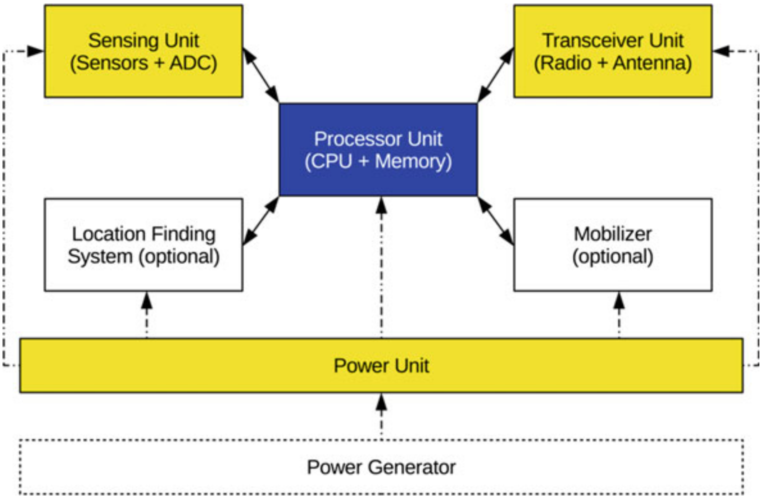


Fig. 13 Architecture of a single-core node

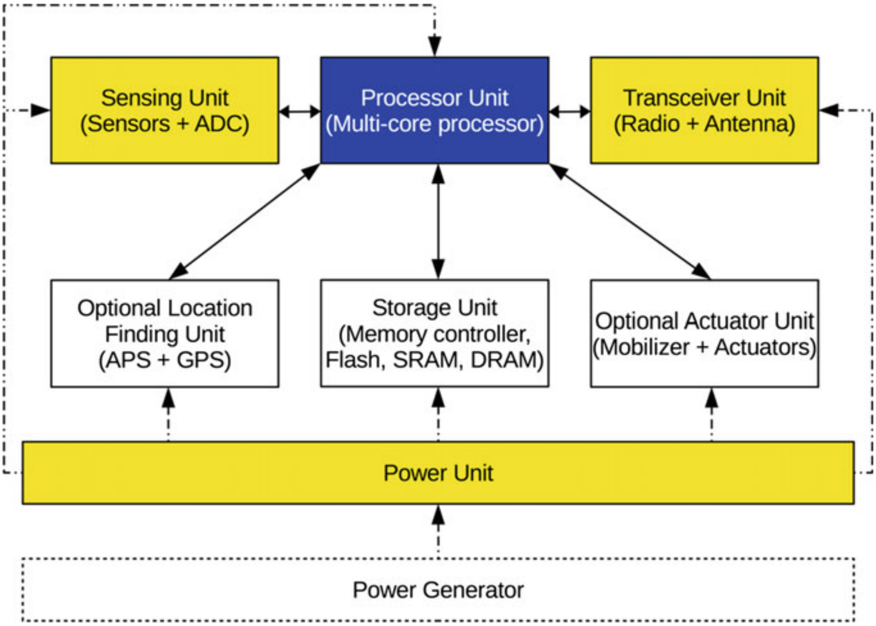


Fig. 14 Standard node multi-core architecture

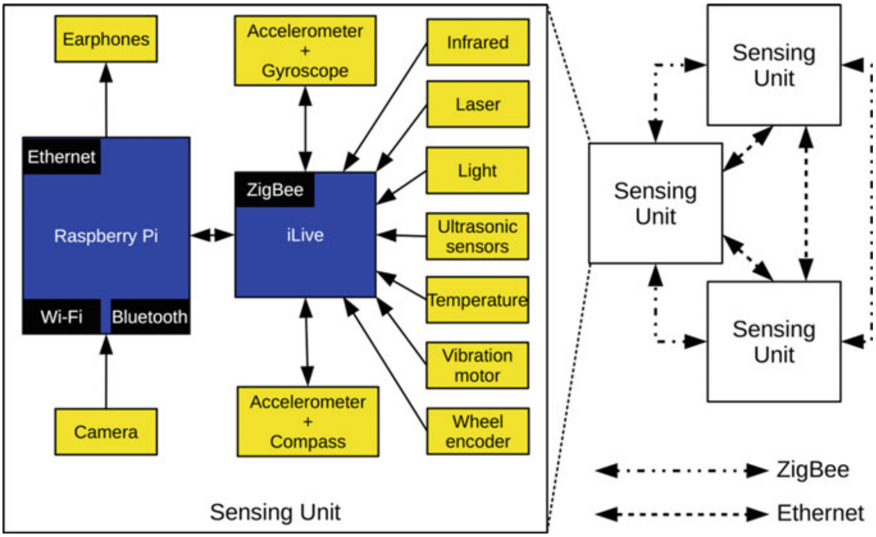


Fig. 15 LMSC prototype and its asymmetric multi-CPU architecture

The LMSC prototype is composed of three sensing units connected through Ethernet and ZigBee. Most of the time only one of these sensing units is active, but when the system needs more computing power or more memory, the three units can work in parallel.

A sensing unit is composed of a Raspberry Pi [92], an iLive module [93], and a cluster of sensors (including accelerometers, camera, compass, gyroscopes, temperature, infrared, laser, light and ultrasonic sensors, and wheel encoder). Some possible technologies to be integrated in any cluster of sensors of an eETA and their key features are listed in Table 1.

The Raspberry Pi is connected to the camera and to the earphones. It is in charge of tasks that need lots of computations, as, for instance, complex fusion algorithms for decision-making, image processing, speech processing, Wi-Fi, or Bluetooth communication with the smartphone.

The iLive module is a low-power consumption sensor node developed by the SMIR group of LIMOS UMR 6158 CNRS [90].

We use a cluster of sensors to increase the robustness of results given by our LMSC. One sensor is not enough to provide good results because no sensor is 100% reliable (see Table 1). For obstacles detection, for instance, we mainly use four sensors: camera, infrared, laser, and ultrasonic sensors. Temperature and light sensors are used in addition to confirm the results given by these sensors.

Table 1 Key features of the different technologies that may be used to implement an eETA

Key components	Functionality	Response time	Cost ($)	Form factor	Energy consumption	Accuracy	Range
US	Obst. detection	~50 ms	~25	★★☆	★★★	★	15 cm–6 m
IR	Obst. detection	~25 ms	~10	★★	★	☆	1–5.5 m
Laser	Obst. detection	~30 ms	~350	☆	☆	★★☆	0–50 m
High-speed laser	Obst. detection	~30 µs	~450	★	☆	★★☆	0–50 m
Laser range finder	Obst. detection	~200 ms	~100	★	☆	★★☆	15 cm–2 m
Camera module	Obst. detection and recognition	~250 ms	~30	★★☆	☆	★☆	~10 m
USB camera	Obst. detection and recognition	~250 ms	~80	★★	☆	★☆	~10 m
Stereo camera	Obst. detection and recognition	~250 ms	~160	★★	☆	★★	~10 m
GPS	Loc., travel distance and speed	100 ms	~30	★★☆	★	☆	Everywhere
Magnetic rotary encoder	Travel distance	~96 µs	~10	★★☆	★	★★★	Everywhere
Gyroscope	Travel distance, navigation	~5 ms	~2	★★★	★★★	★	Everywhere
Accelerometer	Motion, speed, distance	~5 ms	~2	★★★	★★★	★	Everywhere
Compass	Navigation	~5 ms	~2	★★★	★★★	★	Everywhere
Light	Env. context-awareness	~100 ms	~3	★★★	★★★	★★★	Everywhere
Air temperature	Env. context-awareness	~1 s	~2	★★★	★★★	★★★	Everywhere
Humidity	Env. context-awareness	~1 s	~2	★★★	★★★	★★★	Everywhere
Air pressure	Env. context-awareness, location (e.g., change of floor)	~300 ms	~2	★★★	★★★	★★★	Everywhere
Buzzer	Danger signaling	<1 ms	~2	★★★	★★★	★★★	Everywhere
Vibrator	Event signaling	<5 ms	~4	★★★	★	★★★	Everywhere
Low-power Wi-Fi	Network connection, localisation	~100 ms	~15	★★	★★★	☆	Indoor 10–20 m, Outdoors 100 m
Bluetooth ZigBee and 6LoWPAN	Network connection, localisation	~100 ms	~10	★★★	★★★	☆	Indoor 10–20 m, Outdoors 300 m

Each attribute of a component is roughly rated by a star number: the higher the number of stars, the more appropriate the component is to be used in an ETA device. Notice that black stars (★) are better than white stars (☆)

3.2 Software Architecture

The software architecture of sensor nodes is made up of three basic components: the operating system (OS), the protocol stack, and the application, which are described below.

3.2.1 Operating System

The operating system serves as a link between the hardware layer and the application layer of a node. It provides the drivers of the hardware components and manages the memory and the tasks. It can provide an API or middleware to facilitate the development of applications. As already stated, sensor nodes are low resources devices: they have a limited computing power, low energy reserves, and in general are not real-time constrained. Therefore, the eETA cannot use classical operating systems like Windows, Linux, or Mac OS X. Specific operating systems are needed.

Currently, there are three types of WSN operating systems: multithreaded, event-driven, and hybrid-embedded systems. Most of WSN OS are multithreaded or event-driven. Multithreading allows better exploitation of the available hardware parallelism.

Multithreaded OS are real time and have a large memory footprint. Event-driven systems are not real time but have a small memory footprint [94]. Some examples of multithreaded OS are the following: MantisOS [95], DREAM [96], and SDREAM [97]. Some examples of event-driven systems are the following: TinyOS [98], Contiki [99], and SOS [100]. To try to enjoy the best of both worlds, few hybrid OS have been developed. TinyOS with TOSTThread [101] and Contiki with multithreading [99] can execute a real-time scheduler on the top of the event-driven scheduler. MIROS [102] can execute a real-time scheduler in parallel of an event scheduler.

All these operating systems have been introduced for mono-core architecture sensor nodes. Today, no operating system is well adapted to multi-core architectures: their schedulers are not designed for parallel programming and they are not adapted to the context-aware mechanism. Only DREAM and MIROS offer some mechanisms to develop fault-tolerant applications.

In conclusion, no current system exactly corresponds to the needs of the LMSC, which explains why our prototype uses a hybrid system composed of a Xenomai [103], a real-time LINUX (on Raspberry Pi), and a MIROS [102] real-time OS on the iLive board [90].

3.2.2 Protocol Stack

The protocol stacks used on desktop computers (Fig. 16) are not well adapted to nodes used in wireless sensor networks. Their footprints are too large and they

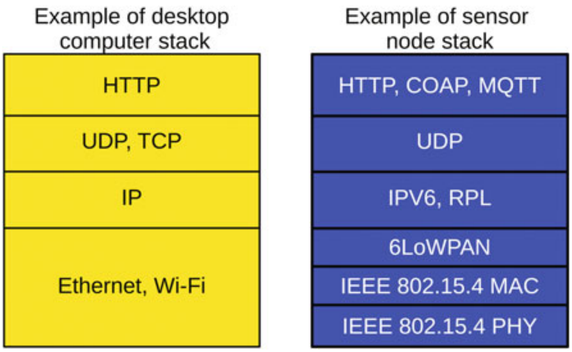


Fig. 16 Typical sensor node protocol stack

consume too much energy for data transmission. In the last few years, many new protocols and architectures have been developed to try to solve these problems: 6LoWPAN [104, 105], RPL [106], COAP [107], MQTT [108], and REST [109].

Our prototype uses a tiny Ethernet/Wi-Fi desktop computer stack in each Raspberry Pi and a ZigBee sensor node stack in each iLive module.

3.2.3 Application to the Design of the Local MIMO Smart Cane Prototype

The main role of the application running on the LMSC is to fetch data from the sensors, the networks and the smartphone, and to process them to output the expected guidance, obstacle or dangers alerts, and informational messages to the VIP. When performing these tasks, the application has to satisfy real time, dependability, and energy constraints. The chosen solution requires to carefully design the application to control heterogeneous redundant and parallel hardware according to the context. Context can be used to control the hardware in several situations:

- If the application "has a doubt" about one result, it can compute it again using other components. For instance, if a distance measured by an ultrasonic sensor is not coherent with the measurement of the same distance by an infrared or laser sensor, the software can start up the camera to process the image to know whether there is an obstacle or not. Otherwise, the camera would normally be off in order to save battery life.
- In situations where the system needs to perform heavy computations, it can wake up one or several processors. Extrapolating the previous example, images from the camera have to be processed in order to extract information of obstacle presence. If it were executed on a very low-power microcontroller, the machine vision algorithms would deteriorate the assistive device performances; the

application should thus start one or more stronger processors, like those of the Raspberry Pi (ARM).

- Finally, the application may need to wake up components in cases of failures. All important vulnerable components being redundant, if one comes to fail, the system can wake up another identical component and use it instead. One difficulty is the detection of failures; for instance, processors can regularly send "heartbeats" (dummy messages) to each other to indicate that they are running and not blocked. But other solutions may also be investigated.

Most of the tasks performed by the processors will be data or information fusion, in one form or another. Data from the sensors are of different nature and quality; they sometimes can be redundant or conflicting; in these cases, fusion can be used to enhance accuracy or to obtain a better confidence in the results. Data or information fusion may provide additional value in three ways [110]:

- Complementarily: the different sensors or information sources describe different parts of an identical quantity;
- Competitively: the sensors or information sources describe the exact same quantity. This mode of fusion gives more accuracy;
- Cooperatively: the sensors or information sources are used to build more complex information than what they describe individually.

The sensors embedded in the LMSC offer the ability to cover the three fields. However, they inherently provide imperfect data (e.g., inaccuracy of measurement, integration drift, missing data) related to their physical characteristics and application environment. Among the existing information fusion methods, the most popular for multi-sensor applications are probabilistic methods, evidence theory, and fuzzy set theory, as they allow representation of imperfect information.

Probabilistic methods are generally based on Bayes' rule and time series. Bayesian inference characterizes likely reasoning under uncertainty. It uses earlier observation to predict or rectify later observations, and models to refine the estimate as new data arrive. Kalman filters, Sequential Monte Carlo methods (SMC), and Markov Chain Monte Carlo methods (MCMC) all rely on Bayesian inference.

Evidence theory, or Dempster-Schafer theory [111], is suitable for working on uncertain data, as it represents all the possible "hesitations" between possible discrete states of a system (e.g., an object can be a "cup", a "glass", or a "cup or glass"). Rules are used to compute belief and plausibility measures for every possible proposition; the interval between the two is the uncertainty over the confidence that the system has in the proposition. Rules exist to fuse belief and plausibility of a proposition according to the information coming from different sources.

These methods are not trivial to implement: Bayesian methods and Monte Carlo methods in particular have high computing power requirements; this stands in opposition with the battery life requirement of the LSMC. Active context-awareness is a solution to that problem: when more power is required, the system can start up one or several powerful processors, and stop them when the result has been obtained.

Dempster-Shafer is not directly applicable either: indeed, it works on the power set of discrete possible states; consequently, computations have an exponential (O (n)) complexity, $\lim_{n\to\infty} 2n = \lim_{n\to\infty} n$, with respect to the number of states of the observed system (n). On the other side, as data from the sensors tend to be continuous, a compression of their information is required.

3.3 Case Studies

The static obstacle detection functionality has been implemented in the prototype of SEES [35]. Six ultrasonic transducers, oriented in a semi-circle manner, were user to detect obstacles in two ranges: 0–1 and 1–2 m. When an obstacle is detected, a vibration coin motor alerts the user, with a different vibration frequency depending on the sensed distance to the obstacle (“close” of “far”). Detection of obstacles has been successfully tested from different distances (0.5, 1.5 m) and heights (0.4, 1, 1.8 m).

Localization experiments have been conducted with the prototype of SEES. During early tests, only the wheel encoder and the gyroscope (which was first calibrated with one accelerometer) were used. Trajectories were computed by integrating the distance measured by the wheel encoder and projected on the displacement direction computed from the integrated angular velocity measured by the rate gyroscope. This method proved to be little robust, because of drift error appearing and growing quickly over time. In further tests, a particle filter was used to fuse the data from these two sensors, plus those of ultrasonic sensors, as follows: the predicted motions of particles were Gaussian samples around the trajectory steps computed from the angular speed—measured by the rate gyroscope—and the displacement—measured by the wheel encoder. Then the particles likelihoods were computed with a simple model of ultrasonic propagation that relied on map information. This method gave a higher accuracy than the former one; however, it was demanding in resources and sensible to the quality of ultrasonic range measurements [28].

A door detection functionality has also been developed for the SEES prototype [28]. Hue–saturation–value (HSV) thresholds were used together with edge detection to recognize doors in the laboratory building. This technique, combined with the scaling down of images, allowed an acceptable detection accuracy while requiring low computing resources: on a Raspberry Pi B, the processing of an image took about 40 ms.

Linked to the door detection, a door handle and doorplate detection functionality was implemented on the prototype. They both used the Oriented FAST and Rotated BRIEF (ORB) feature detector. Because of the power required to run detection using ORB, this method was only performed when a door was recognized. Furthermore, a full resolution picture of the door was used, instead of the scaled-down version used to detect doors [28].

Experiments involving connected objects have also been conducted. iLive nodes [90] were used to mimic smart objects, regularly broadcasting an identifier with a IEEE802.15.4 radio. The messages are sensed by the smart stick, which measures the Received Signal Strength Indicator (RSSI) of the messages. Because of the properties of electromagnetic waves, the RSSI decreases with the distance traveled by the signal and with the traversed obstacles. Thus, it can be used as an indicator of both distance and presence of walls between the transmitter and the receiver. A simple inside/outside the room model, based on an empirical threshold, was used to detect which smart objects were present in the room where the smart cane is.

4 Back End

4.1 Functional Specification of a Global Architecture

Back end is a set of functions which gather, store, and structure information which is used by the front-end system. Back end and front end communicate through information services. Back-end information services can be triggered by the mobility process monitored by the front-end sensors (e.g., next positioning while walking indoor) or by an inquiry made by the user (e.g., destination). Hence, back end is the source of stored information for the front end. Such information includes the following:

- public data (e.g., street map),
- proprietary information (e.g., map of buildings), and
- personal information (e.g., the path followed by a specific user).

The above-mentioned back-end functions support both outdoor and indoor mobilities. However, indoor and outdoor differ, and, therefore, they require specific systems (Table 2). In general, the back-end system provides positioning and path planning information to front end. The front-end system can therefore set the position and guide with the highest precision the VIP user.

In the subsequent sections we illustrate architecture and algorithms of back-end services, and provide foundations for their design and implementation. Specifically, Sect. 4.2 addresses outdoor mobility, and Sect. 4.3 considers indoor mobility.

4.2 Back-End Functions for Outdoor Mobility

The back-end services provide event-awareness and accessible itinerary planning to VIPs. To ensure safety, suggested itineraries skip harmful events (e.g., accidents,

Table 2 Back-end typical technologies and main functions

	Outdoor	Indoor	Comments
Dimensions	2D	3D	Buildings have floors. A key information at which floor the user is
Positioning technologies	GPS	Various technologies: magnetic fields and/or wi-fi and/or computer vision	GPS cannot be used Hence, positioning should be based on the relative location against a known point in the building map Various technologies can be used individually or integrated
End-to-end path planning service	Across roads, A* algorithm can be used for walking. However, typical path planning addresses an optimal combination of available/sustainable transport routes (with mobility specificities of the VIP)	Across floors path planning should be based on optimized wayfinding method as Ant Colony Optimization (ACO)	Back-end system fetches obstacles on the path and Front-end system (Smart Stick) detects them in real time and dialogs with the VIP user
Transport management service	Public/Private/shared/walking	Walking/elevators/spatial vehicles (e.g., AGV)	Outdoor map stores routes of public/shared transports. Indoor map stores elevator position and other key POI (stairs)
Event management service	Road/transport disruptions Social events	Floor/elevator disruptions Social events	Events have a space and time extension

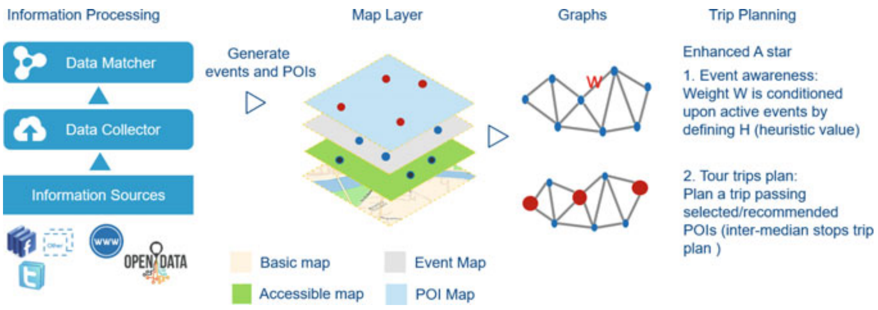


Fig. 17 Overview of back end on outdoor mobility

traffic jam, and parade) and roads that are blocked. Finally, back-end services provide analysis for municipalities and transit agencies (Fig. 17).

In order to support such services, the following data are integrated:

- Events extracted from
  - Social network
  - Web
  - Citizen-sourcing systems
- Point of Interest (POI)
- Data on accessible mobility:
  - Accessible map
  - Accessibility of POIs
- Public transit data:
  - General Transit Feed Specification (GTFS): public transit information which includes timetables, routes, stops, etc.
  - GTFS-real-time feeds, e.g., delays and service alerts.
- Sensor data:
  - GPS.
  - Obstacle detection sensors.

4.2.1 Outdoor Map

Outdoor map is made of several layers, all implemented on OSM (Fig. 18); each layer provides different information on the same space:

- basic map, i.e., the default local street map;
- event map, which displays location and duration of events extracted from multiple data sources;

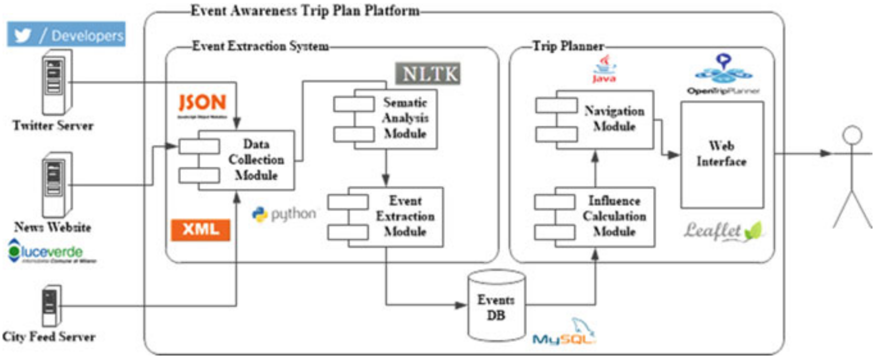


Fig. 18 Event aware itinerary planning

- accessible map, which displays the accessibility of roads, and replaces the basic map when an accessible itinerary planning request is received;
- POI map, showing POI information for VIP, such as accessibility.

Since maps cannot be seen by VIP, APIs (OpenTripPlanner) deliver RESTful web services to front end.

4.2.2 Itinerary Planning

Itinerary planning includes two main services, i.e., (1) event-aware, which in turn includes two modules, namely (1a) event extraction and (1b) trip planner; and (2) accessible itinerary planning services. Let us shortly illustrate them:

Event Extraction Module

It mines events from multiple sources, as (1) online news or public information services about traffic, (2) social networks as tweets from Twitter, and 3) picture-and-text feeds submitted from city issue management systems. The event extraction process is shown in Fig. 19. Here below we illustrate the steps of data collection, sematic analysis, and extraction.

Step 1: Data Collection

Data collection methods reflect the diversity of sources. Public traffic news, which describe events in terms of location, date, and duration, are crawled from relevant websites. Tweets in real time, which include text, timestamp, user profile and, optionally, geo-location, are obtained by APIs. Finally, events from city issue management systems are obtained by web services.

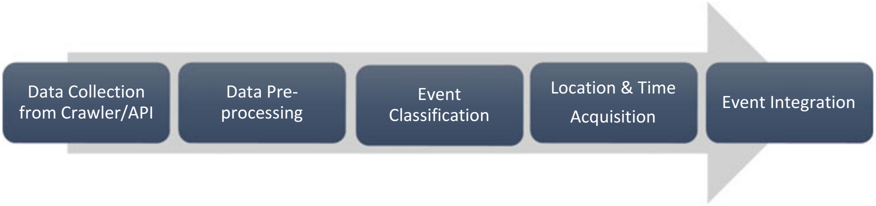


Fig. 19 Event extraction process

Step 2: Data Pre-processing

In pre-processing relevant event news are identified in tweets (and other sources) through the following steps:

- Tokenization;
- Elimination of punctuation, emoji expression, URL link;
- Change of text to lower case; and
- Part-of-Speech (POS) tagging by N-gram tagger;
- Word stemming by semantic analysis through NLTK (Natural Language Tool Kit[5]) or alike methods.

Step 3: Event Classification

Pre-processed texts are grouped. Traffic related keywords are classified by TF–IDF (Term Frequency and Inverse Document Frequency).

Step 4: Time and Location Extraction

First, named entities are recognized by semantic analysis module before extracting attributes of events. For example, the software recognizes which part of the text relates to time and/or location. AI rules and address dictionary, as well as probability estimation are used. Finally, Geo-Encoding API of OSM to associate names and geographic coordinates.

Step 5: Event Normalization

It avoids duplication of events by comparing their attributes of time, geo-location, text, and type. Finally, normalized events are to be used by Trip Planning module.

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[5] Natural Language Toolkit: http://www.nltk.org/.

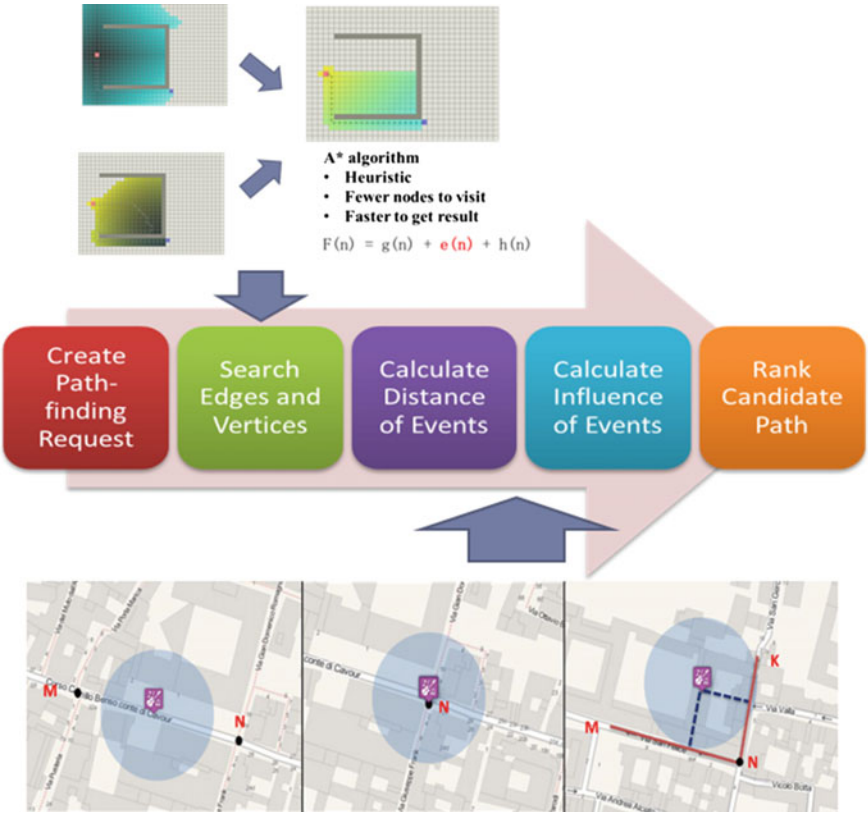

Fig. 20 Event-awareness itinerary planning

Trip Planning Module

It generates multi-modal itineraries that are aware of events and avoid obstacles. It can be implemented on OpenTripPlanner (OTP[6]) or alike platforms. An enhanced A* algorithm considers the impact of events; therefore, the generated itineraries avoid harmful events that may affect itineraries. The overall process is shown in Fig. 20.

The module receives trip time, departure, destination, etc. and it computes the shortest path by pathfinding algorithm and by evaluating the impact of nearby events (Fig. 20); of course the module supports accessible itineraries, which skip steps or obstacles (Fig. 21) by collecting related data as negative POIs interest. Steps include the following:

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[6] OpenTripPlanner: http://www.opentripplanner.org/.

Fig. 21 Accessible trip planning


The normal itinerary

Event-awareness and accessible itinerary

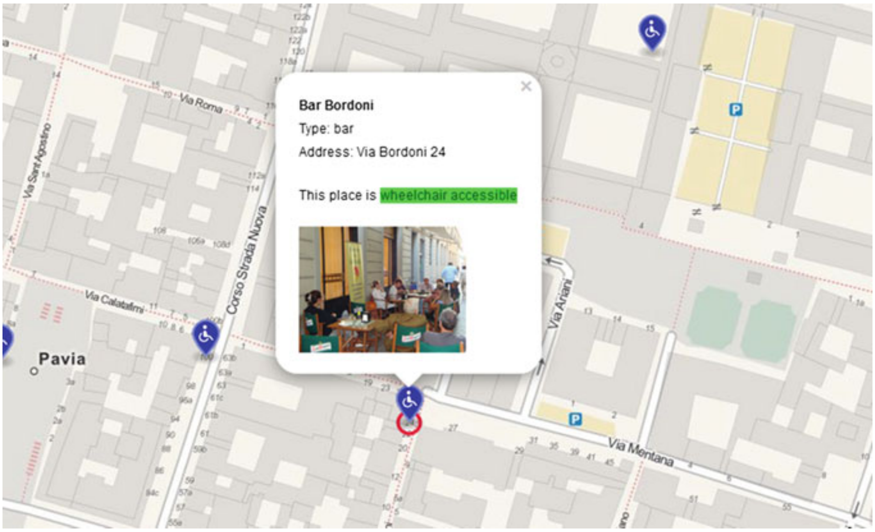
Fig. 22 Example of event-awareness and accessible trip planning

- Find the shortest path from start to end;
- Find out the events along the path;
- If events are going on, check the geographic impact;
- If the impact is relevant, find an itinerary route or re-compute, until the system finds a feasible itinerary, which may be even null.

Figure 22 shows an event-aware and accessible itinerary, which is displayed by front-end applications and web services.

4.2.3 POI Management

POIs are a key issue for VIPs. Indeed, a POI may be (a) accessible, i.e., entrance and rooms without steps; (b) partially accessible, i.e., one step on entrance with a height of 7 cm or less, and most of rooms are without steps; (c) not accessible, i.e.,



Bar Bordoni

Type: bar

Address: Via Bordoni 24

This place is wheelchair accessible

Fig. 23 Accessibility of POIs

entrance step and rooms not accessible; and (d) unknown. Wheelmap[7] is a POI information source for wheelchair users, which contains information on steps/barriers networks. Figure 23 shows accessibility information on POIs.

POI information can be extracted also from generic social networks, as Facebook and Foursquare, and be merged and normalized by clustering (by mapping datasets through a predefined category-based decision tree), matching (by calculating the Levenshtein distances between two POIs), and ranking (by check-in counts information from Facebook and Foursquare).

4.3 Back-End Functions for Indoor Mobility

Back-end functions provide seamless support indoor/outdoor to any user. In particular, a real-time pedestrian navigation in buildings with multiple floors suggests path and POIs. The architecture includes the following (see Fig. 24):

- Indoor Map: a proprietary information of the estate owner organization, which provides static data for positioning and POIs (Maps may be on two/three dimension and are obtained from blueprint or various data models).
- Indoor Positioning: positions the user in a floor within a building, and informs the front-end services; given the constrains of indoor spaces, magnetic fields are used.

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[7] Wheelmap: http://wheelmap.org.

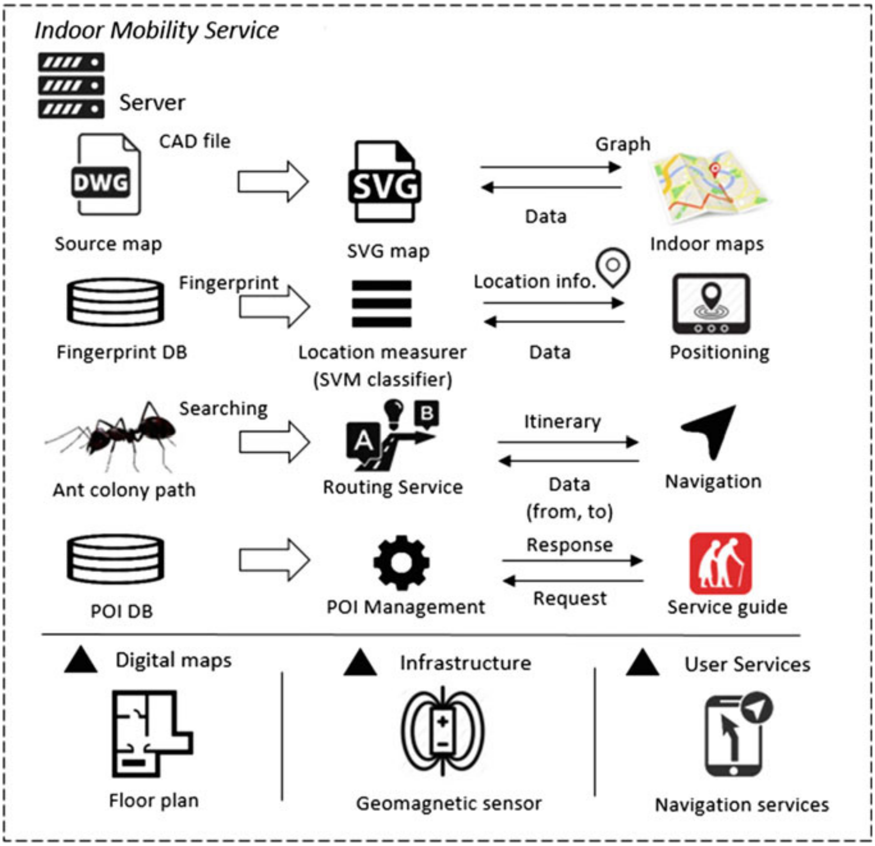

Fig. 24 Overall architecture of indoor navigation

- Indoor Path Planning: calculates an optimal route for indoor navigation based on a specific algorithm (Ant Colony Optimization) and forward directional prompts, such as go straight, turn left, or right.
- POI management: gathers and stores information about POIs in a building, and can link any kind of attachment, like speech clips, text clips, audio clips, etc.

4.3.1 Indoor Map Module

SVG (Scalable Vector Graphics) is used for the indoor map format and Open Street Map (OSM) is used for the base map. SVG fits very well since indoor environment can be updated selectively. Figure 25 shows the indoor map creation process. Finally, the integrated map is uploaded and stored. Metadata group has SVG elements in several layers (Fig. 26). Indoor Map module includes the following:

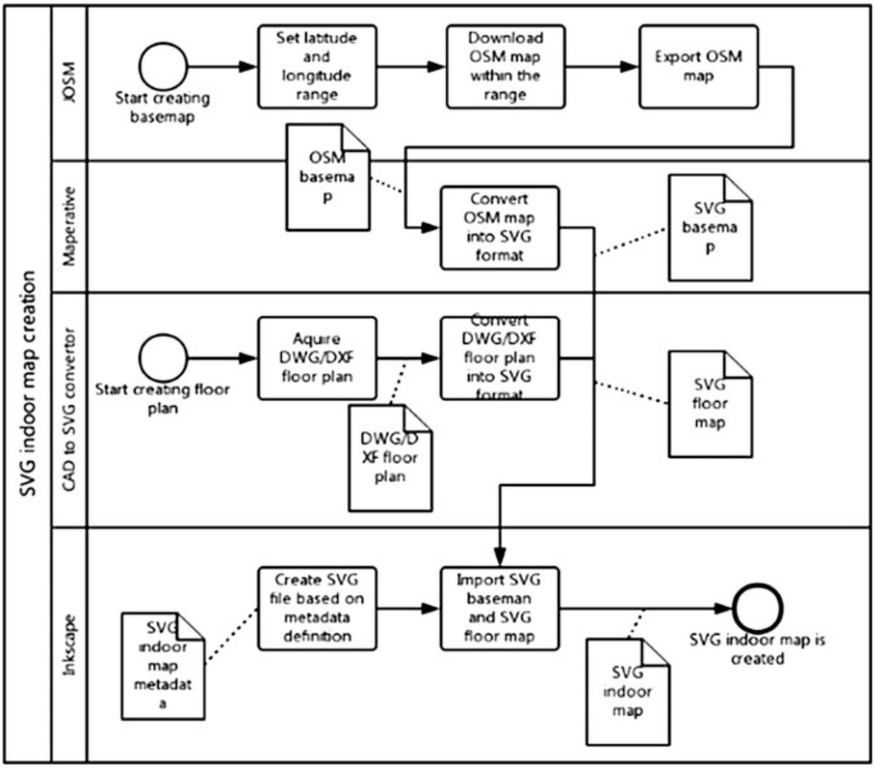

Fig. 25 SVG indoor map creation process

- Export OSM base map: determines the target building, sets latitude and longitude, and extracts the OSM map of the building contour, which is exported by JOSM [112];
- Convert OSM into base SVG by Maperitive [113];
- Convert CAD floor map into SVG: the DWG/DXF floor plan is converted into SVG [114];
- Combine SVG base map and SVG floor map: following the predefined SVG indoor map metadata, the SVG base map and floor map are imported into Inkscape [115] as one file. By integrating the SVG base map and SVG floor plan, an organized SVG indoor map is created.

4.3.2 Indoor Positioning

Indoor positioning is based on Magnetic matching, which includes offline training and online positioning. In offline training, collection and calibration of magnetic data on landmarks and floor plans is the first step. Such calibration removes

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⊞ <svg:g id="Polygons" inkscape:label="Building background">
⊞ <svg:g id="Line_artwork" inkscape:label="Building framework">
⊟ <svg:g id="layer2" inkscape:label="Indoor framework">
     <svg:g id="layer5" inkscape:label="Door">
  ⊞ <svg:g id="layer4" inkscape:label="Room framework">
⊟ <svg:g id="layer1" inkscape:label="Room">
  ⊞ <svg:g id="layer7" inkscape:label="Lab">
  ⊞ <svg:g id="layer8" inkscape:label="Office">
     <svg:g id="layer11" inkscape:label="Classroom">
     <svg:g id="layer12" inkscape:label="Functional room">
  ⊞ <svg:g id="layer14" inkscape:label="Others">
  ⊞ <svg:g id="layer10" inkscape:label="Toilet">
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⊞ <svg:g id="layer13" inkscape:label="Text">
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Fig. 26 SVG indoor map metadata definition

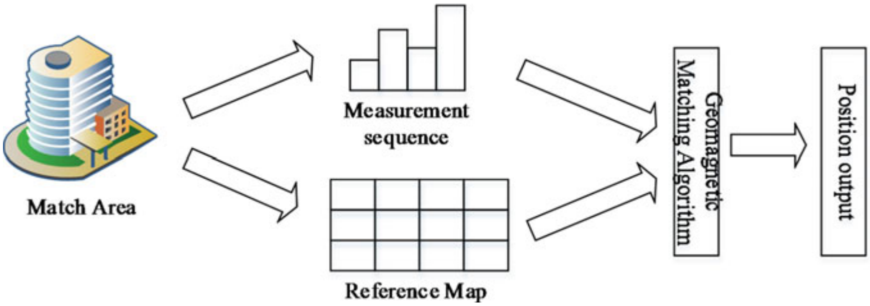
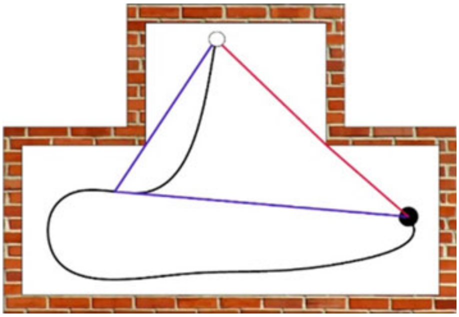


Fig. 27 Schematic diagram of geomagnetic positioning

deterministic sensor errors. Then, the server stores magnetic fields and positions them on the map. Online positioning matches magnetic finger prints gathered by the sensor against the stored map. The sensor transmits a sequence of measurements, and the server replies the best estimated position (cf. Fig. 27).

Fig. 28 Path comparison



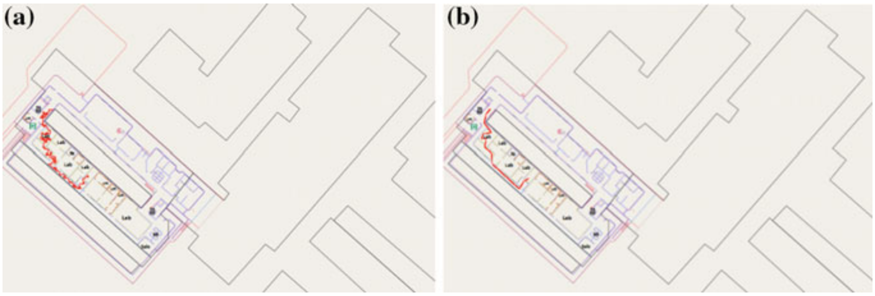


Fig. 29 An example trail on indoor map: left (**a**), right (**b**)

4.3.3 Path Planning

Path planning supports the navigation across floors; it is based on an optimized ant colony algorithm [116]. Ants crawl to avoid obstacles, in turn crawling is influenced by the intensity of the pheromone trails by preceding ants. In a given period, the shorter the distance, the more pheromone left, the higher probability of the shortest way. However, in the basic ant colony algorithm, ants go around and around to find the way. In our ant colony optimization (ACO), we connect by a straight line the current point and the farthest point that does not touch a wall. When we find the farthest point that does not touch a wall, we continue to search within next 200 points, until we find only points that touch walls (cf. Fig. 28: black line is the basic ant colony path, blue line is based on initial idea, and red line is further optimized).

The solution has been tested on a building of University of Pavia. Figure 29 shows the example of the non-optimized trail (Fig. 29a) and optimized trail (Fig. 29b).

In indoor spaces, ACO looks better than the classic A*. Some results are shown in Table 3: the distance with ACO is shorter than with AC, with an average improvement of 69.9%. The time cost of ACO is slightly higher but still acceptable. We tested 10,000 times a trail and ACO always found the optimal path.

Table 3 Testing results of basic ant colony (AC) model and optimized (ACO) algorithms

No.	Start point (x, y)	End point (x, y)	Time duration of AC (ms)	Time duration of ACO (ms)	AC distance of trail (pixels)	ACO distance of trail (pixels)	Distance reduce rate (%)	Time increase rate (%)
A-1	(89, 98)	(268, 289)	327	429	1384	307	77.8	31.2
A-2	(241, 37)	(360, 170)	851	1020	1086	328	69.8	19.9
B-3	(172, 78)	(269, 224)	432	552	754	234	69.0	27.8
B-4	(141, 77)	(258, 278)	369	492	1189	337	71.7	33.3
C-5	(154, 82)	(275, 135)	281	333	684	231	66.2	18.5
C-6	(247, 214)	(326, 195)	337	381	835	269	67.8	13.0
D-7	(155, 84)	(274, 266)	477	568	777	291	62.5	19.0
D-8	(59, 577)	(419, 361)	436	653	1800	566	68.6	49.7
Aver.	NA	NA	438	553	1064	320	69.9	26.2

4.3.4 Indoor POI Management

The overall architecture of Indoor POI management is shown in Fig. 30; it includes the following:

- Data layer: its stores indoor POI information for business services.
- Business layer: business services run on a Web Server, to handle request, operate on data bases, and provide results to users;
- Presentation layer where user can actively use the system.

In order to achieve a low cohesion, layers are integrated by data flows. Figure 31 shows the screenshots of POI management system.

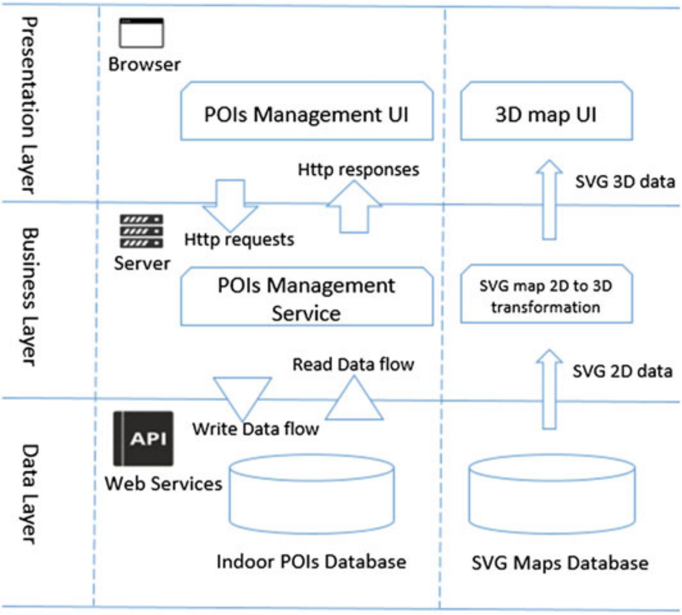


Fig. 30 Overall architecture of indoor POI management system

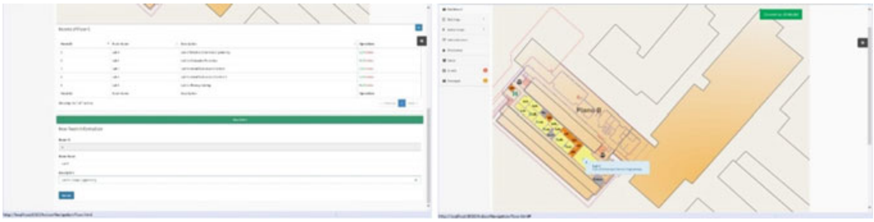


Fig. 31 A POI management screenshot

4.4 Implementation and Deployment

Before discussing the deployment, let us summarize in very simple terms the hardware configuration of the front-end/back-end system. The overall system is made of several interconnected elements, which play front end, back end or both roles: cane, smartphone, communication network, back-end servers.

The cane provides a set of short range sensing functions and communicates with the user as specified in Sect. 1.4.2. The cane, which is the key front-end element, is interconnected with smartphone.

The smartphone enhances the cane functions. The smartphone provides long-range sensing and support functions, and can play the twofold role of front end and back end. As a back end, it can play server functions as path planning. Of course, server functions are bounded by the inherent storage and computation limits. However, those server functions are critical when network and cloud server are not available. The wide range of roles played by the smartphone relies on the very rich sensors of smartphone as magnetometer, accelerometer, compass, camera, etc.

Communication network by different technologies interconnects smartphone and servers; the network is critical in terms of availability, reliability, and scalability. Actually, network context may include Open Outdoor (at least 4 satellites available), Challenged Outdoor (GNSS-hostile outdoor environment as urban canyon), Light Indoor (availability of signal), and Deep Indoor (no satellite in view) [117]. In Deep Indoor context, only WI-FI can be available. And in some case even WI-FI will not be available. So the ability of smartphone to provide services anyway is a key requirement; the system must work even in a downgraded way without network. The scalability becomes an issue if the network is overloaded. Also in this case, the ability of smartphone to provide services is a key.

Back-end servers, in cloud or in premises, store master data as maps, magnetic fingerprints, POIs, etc. They also provide related services to the smartphone.

In this section, we describe how front-end and back-end systems are deployed in order to perform above-mentioned functions. At the end of this section, we describe our practice in deploying services on cloud environment.

4.4.1 Implementation of Mobility Functions

Indoor and outdoor navigation APPs are deployed on smartphones and tablets. Table 4 lists the implemented mobility functions and corresponding back-end services, and involved data. The key features in implementation are also described.

The above-mentioned functions for indoor and outdoor mobility rely on a wide range of data. To support the lifecycle of data collection, integration, processing, analysis, and sharing, an event-driven SOA (Service Oriented Architecture) is implemented. The architecture assembles heterogeneous data and open-source techniques. The data are integrated as layers and can be shared by services.

Table 4 The implemented front-end functions and their supported back-end services

Mobility functions	Back-end services	Data	Key features in implementation
Indoor map management	Map services	Raw indoor map	Map services support the following indoor map conversion functions: 1. OSM/CAD map to SVG 2D map 2. SVG 2D map to 3D map. (details in Sect. 4.3.1) A web portal for map administrators manages the indoor maps. The indoor maps can be downloaded offline from the local server into smart devices when no internet connection is available
Indoor positioning	Positioning services, indoor services	Indoor map (floors), magnetic fingerprints	Positioning services support the online position matching between floor plan and magnetic fingerprints (see Sect. 4.3.2). In offline positioning, a local positioning server in smart devices will synchronize the data from remote servers. The magnetic fingerprints are collected by magnetometer sensors and uploaded to IndoorAtlas and dedicated servers
Indoor path planning	Path planning services	Indoor map (floor)	An Ant Colony Optimization (ACO) algorithm is implemented for indoor path planning (Sect. 4.3.3). ACO doesn’t require the magnetic fingerprints because it detects edges (walls) and accessible path on map images. ACO can also run offline on smartphone when no internet connection is available
POI management	POI services	POIs	POI services collect POIs from social networks through APIs (for outdoor POIs, see Sect. 4.2.3; for indoor POIs, see Sect. 4.3.4). POI services provide a web portal to map administrators to create and edit POIs
AR guide	Path planning services	Magnetic fingerprints, accelerator values	Both outdoor and indoor navigation uses Vuforia AR SDK [118] to create AR guide functions, which contains two main modules: 1. Guide pointer: the guide pointer shows the orientation during the trip. It changes its orientation when values of geomagnetic fingerprints and accelerometer change. The guide pointer and orientation is calculated in smart devices 2. Object detection: objects en-route (e.g., buildings, rooms, shops, bus stops) can be detected and highlighted in the camera view. The software also popups the information on highlighted objects. The images and corresponding information of these objects are to be uploaded to the cloud server of Vuforia using Vuforia AR SDK
Event detection	Event services	Tweets, traffic feeds	Event services are implemented by natural language processing and machine learning techniques to detect traffic events for outdoor navigation (see details in Section “Event extraction module”)
Outdoor path planning	Path planning services, mobility tracking and monitoring services	GPS data, GTFS, Outdoor maps, traffic events	The outdoor path planning is implemented by A* algorithm and considers traffic events to provide event awareness path plans. The path plans are tracking by specific services and dynamically update en-route when new events are detected (see Sect. 4.2.2)

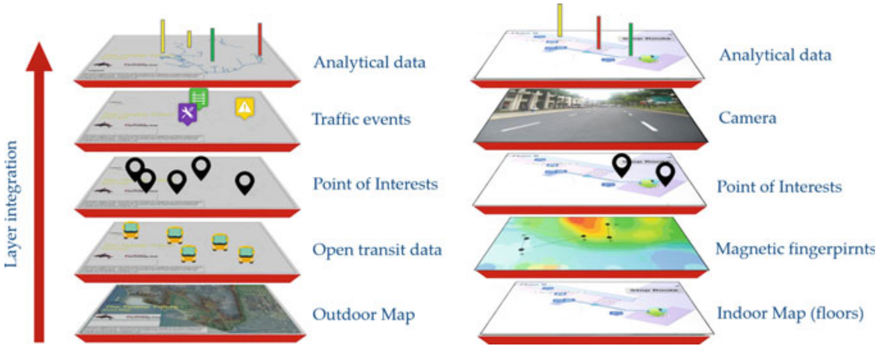


Fig. 32 Data layers for outdoor indoor mobility

Figure 32 shows the data layers for outdoor and indoor mobilities that can be used either individually or together with other data layers.

Figure 33 shows the implementation of the whole architecture and its technology stack. The architecture manages back-end activities by events, which are triggered by requests and the change of data. For example, in back end of outdoor mobility, a detected event/an expired event will trigger the en-route trip rescheduling, which involves multiple layers of data (i.e., map data, accessibility data, event data, etc.) and multiple services (i.e., indoor/outdoor path planning service, mobility analysis service).

Let us illustrate some key practices in optimizing the performance of the above mobility functions.

1. **Online and offline modes—the double servers**: Table 4 shows that most of mobility functions may run offline, without Internet connection. To enable offline availability, a local server is implemented inside the mobile APP, which contains the same basic functions of remote servers and synchronizes data with them. The local server can also reduce the latency, e.g., geomagnetic positioning, object detection by camera. However, due to the limited local storage, the local server cannot cache all the area, and data synchronization should be complete before the user starts the trip. Finally, the load can be balanced on double server. For example, with a low-performance device, the local server will shift the computation to remote servers (if connected to the Internet); when the load of remote server is heavy or the latency of Internet connection is high (i.e., larger than 100 ms, due to the minimal number of geomagnetic fingerprints required in one second is 10), the computation will shift to the local server (offline mode) until new data have to be synchronized or uploaded.
2. **Sensor data streams**: sensor data streams are generated by assistant devices (e.g., connected smart sticks, intelligent canes) and sensors on smart devices (e.g., Camera, GPS, Bluetooth, Magnetometer), which require a high resampling rate. In our case, the resampling rate of geomagnetic field sensor is 100 Hz. To reduce data transmission between front end and back end, a batch processing is

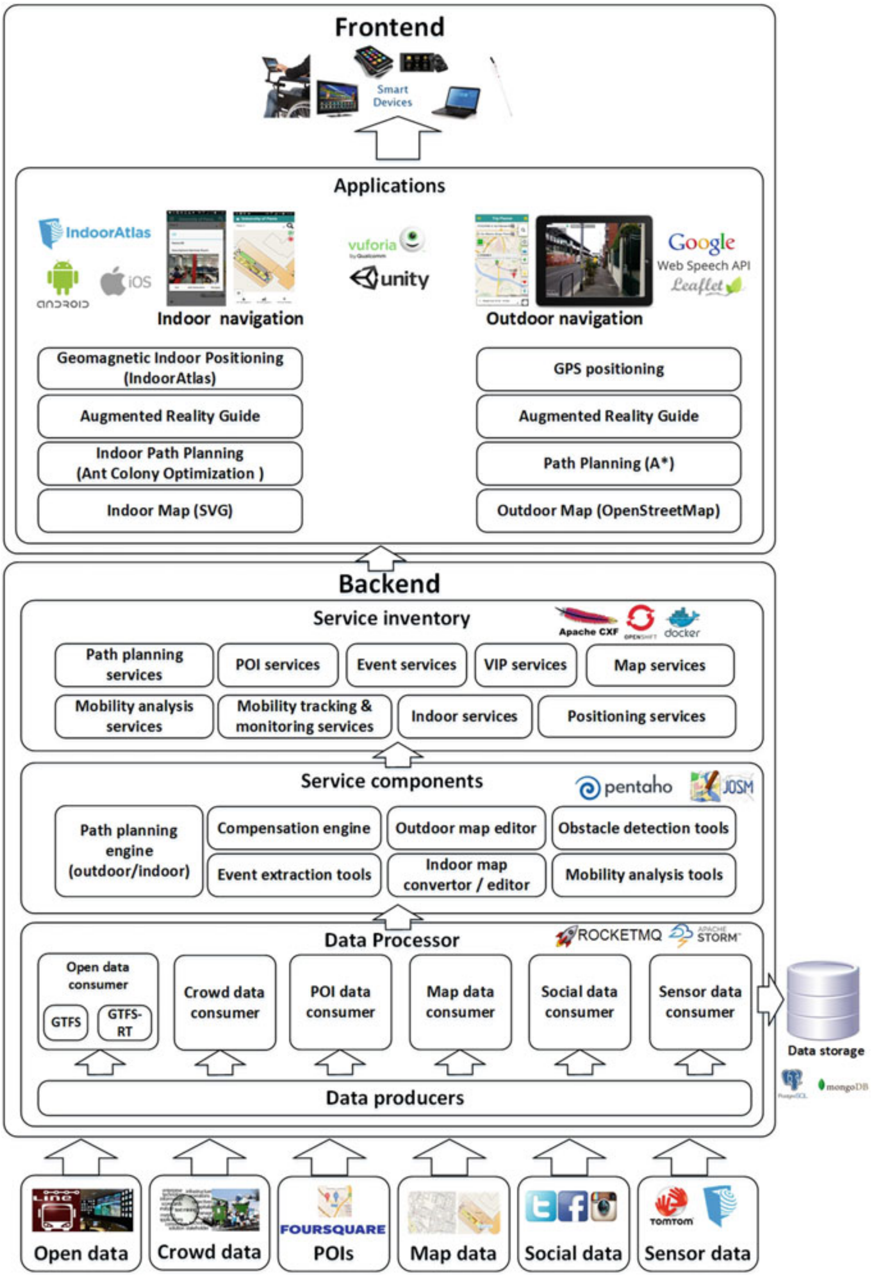


Fig. 33 The implementation of event-driven SOA for back end of outdoor/indoor mobility and its technology stack

performed to generate fingerprints in a certain time interval with a relatively low rate. However, still, at least 10 fingerprints are generated and sent to the back end per device per second for a smooth positioning. In order to process such data streams with low latency, a Publisher/Subscriber model is to be implemented in back end for Event Stream Processing (ESP). This model decouples data producing and data consuming with Distributed Messaging System (DMS), a middleware between data and data processing (e.g., RocketMQ [119]). Thanks to Distributed Stream-based Processing Engine (DSPE, e.g., Apache Storm [120]), the sensor data streams can be distributed processed in real time/near real time (e.g., less than 10 ms). In our test, one 8-core 8G RAM server can process up to 2000 sensor records (4 KB each record) per second, i.e., about 200 clients are online at the same time.

4.4.2 Deployment of Back-end Servers

To support a scalable, consistent development and deployment for such architecture, container technology (e.g., Docker [121]) is to be used and deployed on cloud environment. The container technology reduces the burden of distributed deployment by automating the configuration of processes, and providing a kind of configuration management system [121]. Of course, the cloud environment can scale up the system performance for the distributed computing on sensor data streams in an easy way, a rather essential feature in outdoor and indoor mobility systems.

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Accessible Interactive Maps for Visually Impaired Users

Julie Ducasse, Anke M. Brock and Christophe Jouffrais

1 Introduction

1.1 Context

Mobility and orientation are among the greatest challenges for visually impaired people. In France, 56% of the visually impaired population state that they face difficulties when walking outside and 29% are not able to navigate on their own [12]. One reason that explains these issues is that visually impaired people usually exchange verbal descriptions of itineraries, which may help them find their way, but does not provide them with any clue about the spatial layout of the targeted environment. GPS-based systems, although facilitating navigation, raise the same issue. Sighted people usually acquire information about a spatial environment through visual perception or using geographical maps. However, maps are essentially visual and thus inherently inaccessible for visually impaired people. Limited access to maps has drastic consequences on mobility and education, but more generally on personal and professional life, and can lead to social exclusion [84].

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Beyond orientation and mobility purposes, maps are very useful tools to explore and analyze geographical data and to acquire general knowledge about many subjects such as demography, geopolitics, history, etc. They are also often used in the classroom for this purpose. As stated by O'Modhrain et al. [80], "there is an immediate need for research and development of new technologies to provide non-visual access to graphical material. While the importance of this access is obvious in many educational, vocational, and social contexts for visually impaired people, the diversity of the user group, range of available technologies, and breadth of tasks to be supported complicate the research and development process."

In specialized education centers for visually impaired people, tactile maps are commonly used to give visually impaired students access to geographical representations. However, these materials are rarely used or available outside of schools, because their production is a costly and time-consuming process [97]. To create a tactile map, one of the most common methods is to print it on a special paper, called "swell paper" (synonyms are "microcapsule paper" or "heat sensitive paper"), which contains microcapsules of alcohol in its coating. When the paper is heated, the microcapsules expand and create relief over black lines (Fig. 1a). The resulting maps, called raised-line maps, can be perceived by touch. But they are also visual maps, making it possible to share information between blind and (partially) sighted people. Raised-line maps are usually prepared with a computer, which makes it possible to print and fuse several copies of the same map.

Another technique, called vacuum-forming or thermoforming, consists in placing a sheet of plastic over a master made of a variety of textured materials. When it is heated in a vacuum, the sheet is permanently deformed according to the master. Hand-crafted techniques can also be used to produce maps and other graphics. For example, for orientation and mobility lessons, teachers and students construct itineraries or local maps by progressively placing magnets over a magnetic board (Fig. 1b). Students are sometimes asked to replicate the construction, so that the teacher can check that the itinerary has been memorized. Small-scale models made out of wood also exist, alongside graphics made out of paper, cardboard, ropes, etc. (see Fig. 1c). Edman [23] presented a comprehensive summary of production techniques for accessible maps.

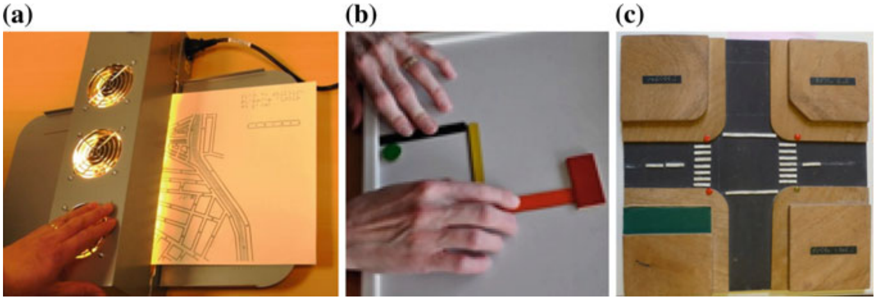

Fig. 1 **a** Production of a raised-line map. The map is printed on swell paper that is passed into a fuser. The relief appears over *black lines*. **b** A simple local map is being built with small magnets. **c** Example of a wooden small-scale model used during orientation and mobility lessons

Although tactile maps are efficient for acquisition of spatial knowledge, they present several limitations and issues. As stated by Rice et al. [97] the production of tactile maps is time consuming and expensive. In addition, tactile maps must be produced by a tactile graphics specialist who knows how to present information so that it can be perceived by touch [114]. Other critiques concern the number of elements that can be displayed and the accuracy of the map content. Indeed, because of the perceptual limits of the tactile modality, less details can be represented on a tactile map than on a visual map. Furthermore, once a tactile map is printed, its content is static and cannot be updated dynamically. Tactile maps are then quickly getting outdated [133]. In addition, the use of braille labels is an issue. Only a small percentage of visually impaired people read braille (National Federation of the Blind [79]); and braille is not so convenient when compared to printed text which can be written with different font sizes and styles. It can be rotated to fit in open spaces. Upper and lower cases, as well as color, can be used to highlight important items. In contrast, braille lacks all of these possibilities and needs a lot of space because it is fixed in size, inter-cell spacing, and orientation [114]. Due to the lack of space, braille abbreviations are commonly used on tactile maps, which are then explained in a legend accompanying the map. Because the reader must frequently move hands between the map and the legend, it disrupts the reading process [43]. Finally, because they are not interactive, tactile maps cannot provide advanced functionalities such as panning, zooming, annotating, computing itineraries or distances, and using filters to facilitate the exploration.

Several research projects have been led during the past three decades in order to improve access to maps using interactive technologies. In this chapter, we first present an exhaustive review of interactive map prototypes. We classified existing interactive maps into two categories: *Digital Interactive Maps (DIMs)* that are displayed on a flat surface such as a screen; and *Hybrid Interactive Maps (HIMs)* that include both a digital and a physical representation. In each family, we identified several subcategories depending on the technology being used. We compared the categories and subcategories according to cost, usability, and technological limitations. Then, because evaluation is essential in order to verify that devices are usable, we reviewed a number of studies showing that they can support spatial learning for visually impaired users. In the following section, we discussed the similarities and differences between maps and other types of graphics (such as bar charts, organigrams, etc.) Finally, we identified new technologies and methods that could improve the accessibility of graphics for visually impaired users (e.g., shape-changing interfaces and 3-D printing).

1.2 Important Notions

1.2.1 About Accessible Interactive Maps

Definition and characteristics of accessible interactive maps

In this chapter, we use the term “map” as suggested by Montello [77]. Montello defines four psychological spaces (i.e., space as perceived by a human) that depend on "the projected size of the space relative to the human body." *Figural space* is "projectively smaller than the body" and can be apprehended without moving. Within figural space, *pictorial spaces* are small flat spaces (i.e., maps) and *object spaces* are 3-D spaces (i.e., small-scale models). *Vista space* is "as large as or larger than the body" and can be apprehended without moving (e.g., town squares). *Environmental space* is "projectively larger than the body" and requires locomotion to be apprehended (e.g. cities). *Geographical space* is "much larger than the body" and cannot be apprehended through locomotion (e.g. countries). Maps are then pictorial spaces that represent environmental or geographical spaces.

Maps can have different purposes. Reference maps support orientation and mobility, by providing for example the possibilities to explore unknown areas, acquire an overview of the surrounding of a landmark, localize specific landmarks, or prepare a journey. You-are-here (YAH) maps are reference maps showing features in the immediate environment of the map reader [78]. They normally include a symbol representing location, and possibly orientation of a person reading the map.

Other map types include topological maps showing selected features without necessarily respecting distance, scale and orientation, as well as thematic maps giving qualitative or quantitative information on a specific topic [23]. Choropleth maps are a subset of thematic maps in which the shading of areas indicates the value of a specific variable [140]. Map representations are not perfect representations of the environment. Deformations occur when the cartographer transforms spatial data into a map representation. The different map types can be used for teaching geography, but also politics, economy, history, etc.

These observations apply to maps made for both sighted and visually impaired users. However, even though purposes and motivations for using maps are similar for both groups, the map representations are different. They are essentially visual when designed for sighted users, whereas they are based on auditory and tactile cues when designed for visually impaired users.

Map data versus map representation

We distinguish between map data and map representation. The map data is usually stored in a database and cannot be explored as it is: it consists in a set of locations (cities, landmarks, streets, etc.), each being determined in absolute terms—latitude, longitude—or in relative terms—in comparison to a reference point [67]. The map data needs to be rendered in a perceptible way, with visual, haptic, tactile, or auditory cues.

When the map data is represented in the form of objects that one can explore by touch, we consider that the map representation is physical (e.g., raised-line maps, 3-D printed maps, maps built using magnets, etc.). If such a physical representation is also associated with a digital representation, we consider that the map representation is hybrid (e.g., an interactive tactile map). When there is no physical representation associated with the map, we considered it as digital (e.g. an auditory map explored with the finger).

Accessible Interactive Maps

In this chapter, the term "interactive maps" refers to all the devices that have been designed to display *pictorial spaces*, as defined by Montello [77]. The interaction relies on technologies that provide feedback in response to user's input. Accessible Interactive Maps are designed for visually impaired users. The family of "touch-enabled" devices has been widely used to design Accessible Interactive Maps. They refer to different technologies that directly sense the user's touch input. They have also been called touchscreens or touch-sensitive devices. Some of these devices are mono-touch (e.g. digitizer tablets, older touchscreen models), but most of the current ones are multi-touch (e.g. tablets and smartphones). Some devices react to bare fingers, whereas others require a pen for input (e.g., digitizer tablets). These devices vary in scale, from smartwatches to large tabletops.

1.2.2 About Touch

Sense of touch

The terms "touch," "haptic," "tactile," etc., are used in many scientific fields including human–computer interaction and psychology, but with slightly different meanings. Here, we more likely refer to the literature in psychology for their definition.

The sense of touch relies on the somatosensory system, which includes thermoreceptors, mechanoreceptors, chemoreceptors, and nociceptors. Tactile (or sometimes touch) perception concerns the contact between the skin of any part of the body and other objects. Because of the presence of different receptors in the skin, muscles, and bones, the sense of touch provides cues on temperature, pressure, movement, and pain.

Cutaneous perception refers to the perception of an object applied onto the skin in absence of any movement. It includes temperature, pressure, and pain. Kinesthetic perception (perception of movement) is based on the deformation of mechanoreceptors in muscles, tendons and joints, such as in the hand-arm-shoulder system [29]. It can also rely on the efferent copy of the movement that is being performed. The kinesthetic perception provides feedback on the current position, and movement of body parts. Kinesthetic feedback can also be referred to as proprioceptive feedback.

Haptic perception has been defined as the combination of cutaneous and kinesthetic perceptions in a complex manner across space and time [29, 40]. It is a dynamic process that combines the cutaneous perception with movement, for instance when actively exploring an object or a pictorial space. Cutaneous perception is referred to as "passive," and haptic perception as "active" [63]. In the field of human–computer interaction, "haptics" has recently been used to describe any form of interaction involving touch.

Point(s) of contact

In this chapter, a "point of contact" refers to the map location that is currently being explored, either indirectly, by the means of a pointing device, or directly, by the user's hands or fingertips. The number of points of contact that can be simultaneously tracked depends on the technology being used. For example, when exploring a Digital Map with a regular mouse, users rely on a single point of contact. On the contrary, several points of contact are simultaneously available when users directly explore a Physical Map with both hands.

Tactile exploration

Many cognitive processes are demanding during tactile exploration of a map. For instance, vision allows the immediate estimation of the relative position of two objects (distance and orientation between them) on a map. This is not the case during tactile exploration of a map. Here the same estimation is based on three serial processes including the exploration of the whole map, the localization of the items displayed on the maps, and the comparison of their relative position. These processes are based on successive one-handed or simultaneous two-handed movements. For instance, it has been observed that visually impaired people use one finger as a fixed reference point when exploring adjacent parts of a tactile map [129]. Obviously, when constraining tactile exploration to a single point of contact, spatial integration is even slower and more complicated, and leads to more significant cognitive issues [41, 70].

Tactile reference frames

Obviously a map has its own reference frame, but the user exploring the map with the hands will build own mental reference frames. In psychology, a dissociation has been accepted between "egocentred" and "allocentred" frames of reference [see, e.g. 63]. In the egocentred reference frame, coordinates of items, and hence distances and directions, are specified relative to the person who is exploring the map. In the allocentred reference frame, coordinates are attached to an external landmark within the display.

Human vision provides both egocentred and allocentred coordinates simultaneously because objects are perceived in relation to the retina but also in relation to each other. This process is automatic and immediate. It is harder to construct both egocentred and allocentred reference frames by touch. Touch is by essence egocentred, and primarily attached to the part of the body that is in contact with the map (usually the hand). Then the origin of the egocentred reference frame is the user itself, and it is more reliable if the user does not move (i.e., change of location relative to the map). In order to build an allocentred mental representation of the map, it is mandatory to explore many items successively. The origin of an allocentred reference frame must be a static tactile landmark on the setup. Finally, because touch is a serial process that relies on direct contact with the various elements of the map, spatial integration by touch, regardless whether it is egocentred or allocentred, needs time.

1.3 Motivation and Method for the Classification

Since the first accessible interactive map prototype has been proposed by Parkes [83], many researchers have designed interactive maps using a variety of technologies and interaction techniques. The current book chapter is an attempt of structuring the work that has been conducted on accessible interactive maps until today. Of course, we acknowledge earlier surveys of interactive maps, which fed the current work. For instance, Zeng and Weber [138] classified interactive maps for visually impaired people in four groups: (1) “virtual acoustic maps” are entirely based on verbal and nonverbal audio output (for instance, the user interacts by tapping on a tablet which then produces audio feedback); (2) “virtual tactile maps” make use of haptic devices (e.g., a force-feedback joystick or mouse); (3) “braille tactile maps” are based on the use of dedicated raised pin displays; and finally, (4) “augmented paper-based tactile maps” use a raised-line map as overlay over a touch-sensitive display combined with audio output. More recently, Kaklanis et al. [54, 55] presented an overview of accessible interactive prototypes. This survey contained map prototypes as well as other accessible graphic tools. In the current survey, we propose a classification limited to interactive maps but including more recent map types, for instance Tangible Maps for the visually impaired, and covering a higher number of references to research projects.

Except in the above mentioned references [138], we did not observe any attempt to more precisely define a terminology to refer to the different types of accessible interactive maps. Various names have been chosen in different publications, and there is rarely an explanation about the choices that have been made. Several authors used the term “audio-tactile maps” [47, 74, 81, 82, 125]. In general, but not systematically, this term refers to maps that are based on touch-enabled devices with audio output. Frequently, but not systematically, “audio-tactile maps” are based on raised-line map overlays augmented with audio output. The term “virtual tactile maps” has also been used to refer to the same kind of prototypes (1999). Some authors referred to different prototypes, based on haptic devices and audio output, as “haptic soundscapes” [33, 61]. In fact, there is no overall agreement about the nomenclature of accessible interactive maps.

In this book chapter, we present a comprehensive summary of accessible interactive maps for visually impaired people. We cover a much larger design space than in previous work, and propose a classification and terminology. We performed an exhaustive search with the aim of covering as many relevant publications as possible using different scientific databases (ACM Digital Library, SpringerLink, IEEE Explorer, and Google Scholar). Then, we applied different criteria: first, we only considered interactive maps that were designed specifically for visually impaired people. Second, we only included publications in journals or peer-reviewed conferences. Third, publications that proposed concepts without any implementation were discarded. Fourth, if several papers were published on the same prototype, we only considered one publication for each. Exceptions were made if the map prototype has had major changes between successive papers.

2 Classification of Interactive Accessible Maps for Visually Impaired Users

In the current classification, we distinguish “Digital Interactive Maps” whose representation is purely digital (i.e., none of the elements of the maps is embedded into a physical object) from “Hybrid Interactive Maps” whose representations are both digital and physical. In this chapter we did not include maps that are purely physical, i.e., that do not make use of any interactive technology (such as raised-line maps). In the first section we present Digital Interactive Map prototypes according to the artifact used to explore the map (finger, joystick, etc.) In the second section we present prototypes of Hybrid Interactive Maps and classify them into three subcategories: Interactive Tactile Maps, Tangible Maps, and Refreshable Tactile Maps.

2.1 Digital Interactive Maps (DIMs)

DIMs can be displayed on a screen or projected onto a surface. They can be explored with one or many points of contacts, which are either direct (e.g. fingertips) or indirect (e.g. the cursor of a mouse or keyboard). DIMs provide auditory feedback and/or tactile feedback (texture, relief, pressure and/or vibration), according to the finger or cursor position. Most of the regular input devices, such as keyboards or joysticks, do not provide additional tactile feedback. In that case, only audio feedback is provided. More recent input devices can provide additional tactile feedback (e.g. a mouse with braille cell or a force-feedback joystick).

2.1.1 Regular 2-D Pointing Devices

Keyboard

The keyboard is a standard device for both sighted and visually impaired people. It has been used in several DIM prototypes [1, 82, 107, 127, 141].

iSonic [141] was a tool for the exploration of georeferenced statistical data (thematical maps). The map was divided into a 3 × 3 grid. Each cell was mapped to one key of the numerical keypad. By pressing one of the nine keys, users could retrieve data associated with the corresponding region. The arrow keys enabled users to navigate within the map. The keyboard could also be used for zooming. The authors conducted a user study showing that most of the participants used the 3 × 3 keys to navigate the map, while the arrow keys were used to answer specific questions such as finding the adjacent regions. Some participants managed to understand the overall layout of the map using the 3 × 3 navigation keys. This map prototype also worked with a touchpad.

Delogu et al. [20] compared two techniques to navigate a sonified map: a keyboard and a tablet. Users were asked to move the cursor across regions, and listen to auditory information about the current location. Then they had to identify the map that they have previously explored among a set of different maps. The results did not show any significant difference in the map recognition task depending on the type of input device used for map exploration (keyboard or tablet). Both input devices enabled users to build an effective cognitive map. However, the results showed that tablet users were more exhaustive than keyboard users, i.e., they explored a higher number of regions. In addition, tablet users changed the direction of exploration more often and were faster. Delogu et al. [20] concluded that the absence of a reliable haptic reference frame and the step by step displacement when using the keyboard demanded a greater cognitive load for integrating the map configuration.

In many other digital maps, keyboard use was limited to additional functions (i.e., command selection) rather than spatial exploration. For instance, it has been used to change the map heading [107] or to enter commands such as zooming or scrolling [1].

Joystick

Picinali et al. [87] implemented a device that used a regular joystick for navigating a virtual environment. The virtual environment represented a corridor leading to a few rooms as well as various objects (doors, windows, elevators) and 3-D virtual sounds (music, voices, etc.) Footstep noises were played every 50 cm, and finger snapping noises could be triggered by the user at any time to determine the position of objects by listening to the echoes. The navigation speed depended on the pressure applied to the joystick. Results of their user study showed that participants were able to build correct mental representations of the environment, and that these mental representations were similar to those acquired through actual navigation in the real environment. Similarly to the keyboard, regular joysticks do not provide any feedback other than visual regarding the position of the cursor. In addition, the cursor movement is relative to the last cursor position, which is hard to track without vision. Although the results by Picinali et al. [87] were encouraging, joysticks have rarely been used in accessible digital maps.

Tangible pointing devices

In this subcategory, we refer to the use of objects to move a cursor over the map. We do not refer to maps whose representations are embedded into several tangible objects (see “Tangible Maps”). In the specific context of this chapter, we consider the computer mouse as a tangible pointing device.

Only few projects were based on a regular mouse. Earth+[1] is a project developed by the NASA where the user moved the mouse within the map. The visual image was transcribed into auditory feedback, with different colors corresponding to different notes. These notes were then played corresponding to the current cursor

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[1] http://prime.jsc.nasa.gov/earthplus/ [last accessed September 29th 2016].

position. To our knowledge the device has not been further developed since 2009, and remained in beta version. In addition it has not been evaluated with visually impaired users. In fact, it appears that mouse is rarely used by visually impaired people because the feedback concerning the cursor position is primarily visual. In addition, when using a mouse, distortions appear between perceived and real distances [52]. Finally, the mouse can be lifted up and moved elsewhere while keeping the pointer position stationary [61], which generates disorientation when using it in absence of vision [33, 91].

Milne et al. [76] used a pen-based digitizer tablet with a stylus that enabled users to control the position of the cursor within the map. Orientation was controlled by rotating the stylus (a tactile cue on the stylus indicated the forward direction). Daunys and Lauruska [18] used a similar approach. The users explored the map by moving a pen over a digitizer tablet, and non-speech sounds were played accordingly. Brittell et al. [6] also used a similar apparatus to present a choropleth map to visually impaired users, including basic spatial analysis tools. Depending on the position of the stylus, different queries were sent to a spatial database to provide the user with up-to-date content. Different sounds were played to inform the users about the population density as well as to indicate when they were near a border or outside the map. Pielot et al. [88] used a toy as a “virtual listener” that a user could move over a map. A camera placed above the map tracked the object’s position and orientation, and auditory output was given according to its position.

2.1.2 Pointing Devices with Additional Somatosensory Feedback

Visually impaired people are used to both auditory and tactile cues. The aforementioned prototypes provided only auditory feedback, which may limit their ability to convey information. Many DIM prototypes have used pointing devices with additional force or cutaneous feedback.

Pointing devices with force-feedback
Force-feedback devices mechanically produce a force that is perceived as a kinesthetic feedback by the user [24]. Various force-feedback devices have been used for the exploration of DIMs by visually impaired people including computer mice, devices with handles, gamepads and joysticks.

As mentioned before, regular computer mice are difficult to use in absence of vision. Force-feedback mice provide additional tactile feedback that may be helpful [14, 61, 82, 97, 118]. For instance, in the map prototype by Rice et al. [97] a haptic grid overlay and a haptic frame were rendered by a force-feedback mouse. Moving the mouse over the grid produced force-feedback, and allowed users to keep a sense of distance, scale, and direction. The haptic frame around the map served as a barrier to present the map outline. Rice et al. [97] reported that the frame was very helpful for the users as it worked as a reference frame (see Sect. 1.2.2). However, Lawrence et al. [61] observed that users encountered problems regarding spatial orientation with such a device even if a grid was provided.

Other prototypes used gamepads [82, 98] or joysticks [60, 83] with force-feedback. Both are affordable and available as mainstream products. They generally possess a small number of degrees of freedom and moderate output forces [24]. In the BATS prototype [82], the input device provided slight or large bumps when the cursor moved across boundaries, as well as vibrations when the cursor moved over a city. Schmitz and Ertl [98] used the vibrations of the gamepad to indicate when the cursor was in proximity of a street. Users could navigate the map by moving the analog sticks of the gamepad. In the prototype of Lahav et al. [60], users could navigate a virtual environment using a force-feedback joystick. The environment used in their study represented a room with several elements such as doors, windows, and pieces of furniture. Footsteps noises were played during the displacement as well as other sounds (tapping, bumping, names, etc.). Results showed that participants were able to understand the spatial configuration of the room, but also to rely on the build mental map to successfully perform Orientation and Mobility tasks in the real environment.

Other haptic devices rely on a handle that can be moved and eventually rotated in space and that allows interaction in three dimensions. Both the Geomagic Touch X[2]© (formerly the Sensable Phantom Desktop) and the Novint Falcon[3]© are tensioned cable systems, i.e., the handle is moved in different directions by several actuated cables [24]. The user grasping the handle can sense the force that is produced by the device. The Geomagic Touch X provides six degrees of freedom (DoF), i.e., the possibility to vary position and orientation along the three spatial axes, as well as 3-D force-feedback. The Novint Falcon allows only three DoF [24]. Several DIMs have been implemented with these devices. The prototype by De Felice et al. [19] allowed the exploration of indoor environments as well as complex geographical areas. Each element of the map (doors or rivers for example) was associated with a specific haptic feedback. Users could select the content that they wanted to display as well as change the scale and level of details of the map. HaptiRiaMaps [53] was an open-source web application based on OpenStreetMap[4] (OSM). It allowed visually impaired users to search for a specific address, and explore the haptic and audio map around the selected address. VAVETaM (Verbally Assisting Virtual Environment Tactile Maps; see Lohmann et al. [69]) provided visually impaired users with the name of the elements that they were currently exploring and with an additional description of the local spatial layout (for example, “this is the intersection between road A and road B”). SeaTouch [107] allowed blind sailors to prepare a journey by using a DIM that provided haptic feedback, text-to-speech output (TTS) and ambient sounds.

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[2] http://geomagic.com/en/products/phantom-desktop/overview [last accessed September 29th 2016].

[3] http://www.novint.com/index.php/novintfalcon [last accessed September 29th 2016].

[4] https://www.openstreetmap.org [last accessed September 29th 2016].

Iglesias et al. [45] worked with the "GRAB" interface. This device creates 3-D force-feedback, but in contrast to the previously mentioned devices it has two distinct handles. Two fingers, either of the same or different hands, are placed in two thimbles onto which two independent force-feedbacks are applied. Several applications were developed, one of which being a city map explorer application. Observations confirmed that using a second finger "can be vital as an "anchor" or reference point" (see Points of contact in 1.2.2).

Pointing devices with cutaneous feedback
Input devices can also be augmented with cutaneous feedback. The more common devices include mice with an array of pins, in which the pins move up and down according to the cursor location. For instance, the VTPlayer by VirTouch was such a tactile mouse with two 4 × 4 arrays of pins. These arrays were located under the index and middle fingers, and were actuated according to the cursor location. We identified one project [51] that made use of a mouse with an array of pins that were actuated according to outlines and textures. Jansson et al. evaluated this device with 60 sighted blindfolded participants comparing different map representations. They recommended that shapes should be represented without any filling when using such a device. Tixier et al. [117] designed Tactos, a system made of two devices: one pointing device moving over the map, and two fixed braille cells placed on another device on the side. Moving the pointing device determined which information was displayed on the braille cells. Different pointing devices could be used, such as a stylus on a digitizer tablet. To our knowledge, Tactos was not evaluated with visually impaired users.

Latero-tactile displays have been designed quite recently and provide different cutaneous feedback. A latero-tactile display deforms the skin of the fingertip with an array of laterally moving pins actuated by miniature motors [66, 86]. It can evoke perceptions like dots, grating (waves) and vibrations. In a first study [86], the latero-tactile device was used to explore a map with two levels of information: one for the continents and the other for the location of five civilizations. Users could switch between these two levels by pressing a key. In this study, the device was mounted on the Pantograph [15], a haptic device that allows 2-D movement over a limited surface. In another study, Levesque et al. [66] observed nine blind users exploring a concert hall seat plan with a latero-tactile display mounted on a movable carrier. The carrier measured the absolute location of the device. These studies showed that visually impaired people as well as blindfolded sighted people could successfully explore the maps with the device. However, because this device is a research prototype, only few projects made use of it.

2.1.3 Finger-Based Exploration

Finger-based exploration, which we also call "direct exploration", has been used in many research projects. In that case the input device is one of the user's fingers, onto which the position of the cursor is directly mapped. Feedback can be auditory or tactile (vibrations). The location of the user's fingers can be tracked using a touch-enabled device (e.g., digitizer tablets, smartphones, tablet or tabletops) or a camera.

Finger tracking on touch-enabled devices

Because smartphones, tablets and digitizer tablets are mainstream consumer devices, many accessible map projects have used this kind of device. Smartphones and tablets moreover present the advantage of being usable in mobile situations. Large tabletops are more expensive and have been used less frequently. Some projects did not specify the type or size of touch device and might therefore function with different hardware [1, 83].

Several projects relied on touchpads (i.e., single input devices that are commonly used by graphic designers and that enable interaction using a finger or a pen (Fig. 2)). Jacobson's prototype [47] allowed visually impaired people to explore auditory maps by pressing specific areas on a touchpad (north, west, south, east, and zoom buttons). Verbal descriptions, ambient sounds (such as traffic noise), and auditory icons were played during exploration. Five visually impaired and five blind people evaluated this device. All of them were able to use it and found it simple, satisfying and fun. The iSonic project [140] also relied on a touchpad but with an additional keyboard for exploring choropleth maps. When tapping on a region, one of five violin pitches was played according to the choropleth's value within that region. Using iSonic, seven participants were able to solve complex tasks. Participants found the prototype easy to use and helpful.

Fig. 2 Example of a Digital Interactive Map: the map content is displayed on a touch-enabled device. During exploration the device produces audio output

Recently, smartphones have been used. TimbreMap [109] was a sonification interface for exploring floor-plans of buildings. Stereo auditory feedback indicated the corrective action needed to follow a path on the screen, or the direction that the finger was drifting towards. Six blind participants managed to identify simple shapes with 80% accuracy. One participant performed a supplementary task in which he was able to find all points of interest on two maps of different complexities. TouchOverMap [93] provided a basic overview of a map layout, by giving vibrational and vocal feedback when the finger passed over a map element (e.g., streets or buildings). The evaluation, performed with eight blindfolded sighted users, showed that all participants acquired a basic understanding of the "zoomed-out" and "zoomed-in" version of a map, even though they found the "zoomed-out" condition difficult.

Several projects relied on the use of tablets that are larger than a smartphone but smaller than a computer screen. Simonnet et al. [106] designed a tablet application with auditory and vibrational feedback. Carroll et al. [16] described the design of a weather map of the USA for visually impaired users. When the user moved his/her finger over the tablet, a TTS engine pronounced the name of the states and different musical notes were played to convey temperature values. When the user was touching a state containing a minimal or maximal temperature, the device vibrated. Double-tap was used for zooming. The same design was presented by Lazar et al. [62]. Another project called Open Touch/Sound Maps [54] provided visually impaired users with access to OpenStreetMap data using TTS synthesis, vibration feedback and sonification. Vibration and TTS description were executed when the user's finger touched a point of interest. Besides, 3-D auditory cues were provided to indicate the distance between the current finger location and the next crossroad.

In the framework of the BATS project, Parente and Bishop [82] developed two prototypes to enable a blind student to explore a map of Great Britain. The user could explore the map either by moving the on-screen cursor with a mouse or a trackball or by using a touchscreen directly. TTS and spatialized auditory icons were provided. An informal evaluation with one user revealed that he preferred using a trackball to the touchpad. However, an informal evaluation with one user only is not sufficient to draw conclusions.

Few projects have been developed on tabletops. Kane et al. [57] designed three interaction techniques for maps displayed on large touchscreens. In a first bimanual technique called "Edge Projection", locations of map elements were projected onto the x- and y-axes on the left and lower edges of the screen. Users could thus browse the axes to find the names of on-screen targets. When they identified a target, they could drag both fingers from the edges to the interior of the screen in order to locate it. The second technique, called "Neighborhood Browsing", expanded the size of map elements by using the empty area around them. Touching the neighborhood of a map element launched audio feedback pronouncing the element's name. The third technique, called "Touch-and-Speak", combined touching the screen with speech recognition, so that a user could, for example, ask for the list of on-screen targets. Both "Neighborhood browsing" and "Touch-and-Speak" allowed to find a specific target based on spoken instructions. Fourteen blind users compared these three interaction techniques to a regular implementation of Apple's VoiceOver. The results revealed that "Touch-and-Speak" was the fastest technique, followed by "Edge Projection". Furthermore, there were significantly more incorrect answers with VoiceOver than with the other techniques. Users also ranked "Edge Projection" and "Touch-and-Speak" significantly better than VoiceOver. Another tabletop based prototype was designed by Yairi et al. [132] to enable users to follow a line on a map. A line was divided into eight equidistant segments. When the finger followed the line, the successive notes of an octave ('do re mi fa sol la si do') were played according to the segment being touched. The authors asked four blind people to explore a map with streets, and then find a route without assistance. Using this technique, users were able to know the length of each route segment being touched. Interestingly, they were able to anticipate the next crossing when a route was made of many lines. Finally, all participants achieved the goal of finding a route, even though they sometimes made wrong turns or felt lost.

In the Tikisi project [1] the touchscreen type and size was not specified. Users could touch a map and hear the name of the element under their finger (country, road, etc.). They could also zoom in and out, scroll, or select a location. Additional input techniques (keystrokes and speech recognition) were used, and TTS was provided as output. Twelve visually impaired people used the application and reported surprise, enjoyment and interest. However, the study did not report any result about success.

Camera-based finger tracking

Cameras (including webcams, embedded smartphone cameras, stereo cameras or motion capture systems) can be used to detect one or multiple finger(s). In contrast to touch-enabled devices, they may allow to identify each finger. On the other hand, these systems are subject to technical challenges such as lighting conditions and occlusion.

The "KnowWhere" system [59] was composed of a camera mounted above an illuminated table. A sound was played each time the user's fingertip passed over an element. Users could also enlarge a specific area in order to access a more detailed map. Another prototype developed by Schneider and Strothotte [100] allowed the exploration of an urban area as well as learning a route. The feedback was based on both speech and sound. Seisenbacher et al. [102] used a similar set up, but with a color marker attached to one finger and tracked by a camera mounted above a tabletop. When the finger entered an interactive zone, the corresponding sound was played. AccessLens [56] enabled visually impaired users to interact with paper documents including elements with labels. The camera placed above the table was used to decode the labels and recognize the user's gestures. Users were able to retrieve the names of the elements, but also to use a gesture or voice command menu. During the evaluation, five blind users were asked to explore a diagram, a map of the USA, or a table presenting poll results. Qualitative results showed that the participants were highly satisfied with the system and the interaction modes, even if they faced some interaction issues (when placing both hands on the document for example).

Bardot et al. [2] used a motion tracking system to track a smartwatch during map exploration (Fig. 3). Motion tracking allowed both 2-D (exploration) and mid-air gestures (filtering). The smartwatch provided sound and vibrational feedback, in addition to different filtering commands. A two-step guidance function based on vibrations helped users to find specific targets. In a follow-up study, Bardot et al. [3] used a similar set up to track the user's dominant finger. The maps were composed of several areas, each area being associated with a name and quantitative data. Three exploration techniques were designed: the "Plain" exploration technique simply provided auditory feedback when the finger was entering an area; the "Filter" technique relied on filter selection on the smartwatch and enabled the user to select which data to display; the "Grid-Filter" technique combined the "Filter" with the use of a virtual 3 × 3 grid that the user could explore using mid-air gestures. The evaluation, including 12 visually impaired participants, compared the exploration of a regular raised-line map to the exploration of a digital map with these three different techniques. It showed that the exploration of a digital map, without any tactile cues, is possible. It also showed that the "Grid-Filter" technique is efficient for data selection or comparison tasks.

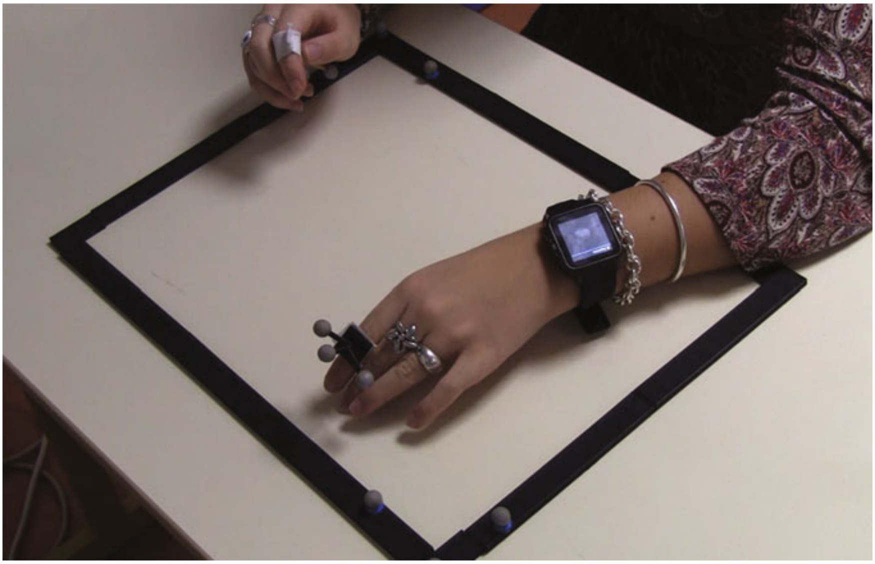

Fig. 3 Example of a Digital Interactive Map: one finger is tracked with a motion-capture system. During exploration the user's smartwatch produces audio output and vibrates

2.1.4 Summary and Conclusions

In this category, we discussed different prototypes that provide visually impaired people with access to digital maps, i.e., maps whose representation does not rely on any physical object as elements of the map. The term “virtual”, which is sometimes used, is appropriate, but should not be used in opposition to visual maps. In comparison to “visual” maps, these maps could specifically be called “auditory” or “somatosensory” maps. We chose to use the term “digital” in order to incorporate in the category all the prototypes with auditory and/or somatosensory feedback (in many prototypes both feedback are used simultaneously), but also to stress the opposition with hybrid maps that combine a physical representation (e.g., raised lines maps, small-scale models, or refreshable displays) with a digital one.

As we showed, only few accessible interactive map prototypes made use of a keyboard. A keyboard is very well adapted to text entry, but is less adapted to 2-D pointing and hence to exploration of spatial data. In the context of accessible maps, keyboards have mainly been used as a complementary text and command input device.

Joysticks are based on the relative displacement of a cursor, which works well with visual feedback. In absence of vision, the location of the cursor must be perceived through specific auditory or somatosensory feedback. The localization of the cursor then causes an additional cognitive task that must be performed by the user. In the prototype of Picinali et al. [87], participants managed to explore a virtual environment with a joystick. But the environment was rather simple (a corridor and a few objects), and it is uncertain if a joystick could be used to explore more complex environments.

In contrast to keyboard and joystick, a tangible pointing device allows the user to point at specific locations on a digital map. The location of a tangible pointing device is perceivable by touch and is trackable with a camera or a touchscreen device. Then no dedicated hardware is required, and if the object does not provide additional feedback (e.g., vibrations) it can be very cheap. Indeed, affordable mainstream devices such as mice, pens and toys can be used with a cheap camera [88].

Many tangible pointing devices provide additional cutaneous or haptic feedback. It has been shown that such feedback may increase usability. For instance, the augmentation of a computer mouse with force-feedback that indicates map boundaries and edges of a grid helped users to maintain spatial orientation [97]. Other pointing devices with tactile displays (e.g., braille cells or latero-tactile display) also enhance map exploration, for example by enabling users to switch between different levels of information [66]. However, these devices are lab prototypes, and hence are not available for visually impaired users. Specific haptic devices, such as the Geomagic Touch X, are on the market, and also provide sensory cues that enhance accessibility. However, they are more expensive than regular pointing devices.

Touchscreens, tablets and smartphones have been frequently used for non-visual map exploration because they are widespread and affordable. They provide a surface on which the map is displayed, which helps the user to select a reference frame (e.g., one corner of the touchscreen), and quickly perceive the spatial extent of the map (it usually corresponds to the size of the touchscreen). In addition, tablets and smartphones can be used in mobile situations, which may be very important for visually impaired users. However, touchscreens do not provide cutaneous feedback associated to the elements that are displayed on the map. They are per se input devices with visual display [11]. In the absence of tactile cues, it is difficult to understand the spatial layout and estimate relationships between elements of the map. It is then necessary to provide additional non-visual feedback for visually impaired users.

Camera-based digital maps provide the same advantages and drawbacks as maps based on touch-enabled devices. However, they highly depend on lighting conditions and occlusions, which make them less usable, especially when they are used in mobility. Finally, maps based on motion capture devices offer enhanced opportunities because they are adapted to the capture of 3-D gestures. They can provide mid-air [2, 3] or complex gesture recognition, but they are much more expensive and need accurate calibration as well as a fixed setting. It is interesting to note that even though some force-feedback devices (e.g., Geomagic Touch X) can detect 3-D gestures, no prototype took advantage of this capability.

In conclusion, digital maps can be explored using a variety of input devices, as well as with touch-and-gesture interaction. Digital maps present many advantages. Depending of the input device that is used, a digital map prototype can be very cheap [e.g., 109] and used in various contexts including home, the workplace, or school. In addition, digital maps can be dynamically updated, and therefore support operations such as panning and zooming. However, the absence of tactile cues during non-visual exploration is an important drawback that must be compensated.

2.2 Hybrid Interactive Maps (HIMs)

As we previously mentioned, Hybrid Interactive Maps (HIMs) are made of a digital and a physical representation. There have been many prototypes in the literature relying on different physical displays. We classified HIMs into three categories according to the type of physical display that was used.

2.2.1 Interactive Tactile Maps (ITMs)

With the term "Interactive Tactile Maps" we refer to physical representations that correspond to tactile maps (see 1.1 Context). In contrast with tangible or refreshable maps, which we will introduce hereafter, tactile maps are static. The content cannot be dynamically updated. The only way to change the map view (zoom or pan for instance) is to change, or erase and redraw the physical representation. In the category of tactile maps, raised-line maps have been extensively used, but more recently 3-D printed maps have emerged. Two different technologies have then been used to track the user's finger(s) over the tactile map: touch-enabled devices or cameras.

ITMs with finger tracking on touch-enabled devices

Up to now, this category only includes Interactive Raised-line Maps but other types of overlays could be considered, such as 3D printe overlays. Raised-line maps have proved beneficial for spatial learning by visually impaired people for many years, and are thus a familiar tool for most of them [121]. Several prototypes relied on this observation, and aimed at making raised-line maps interactive. In those maps, a raised-line overlay is placed over a touchscreen device that allows the detection of touch inputs through the overlay. Users perform taps or double-taps on any interactive element of the overlay, which produces speech, sound, or vibrational feedbacks (Fig. 4).

Parkes [83] was the first to design an interactive raised-line map with an overlay placed over a touchscreen. Even though the technical aspects of his NOMAD prototype were not precisely described, Parkes envisioned that gestural interactions (for example “touching two points for direction and distance interaction”) combined with appropriate auditory feedback could greatly enhance the use of tactile maps. Since then, several research projects have been developed along this direction. The prototype described by Weir et al. [127] presented a weather forecast map of the USA. When the user selected a state by tapping on it, a sound was played whose pitch encoded temperature (the higher the pitch, the higher the temperature). The prototype of Senette et al. [103] provided the names of the streets using a TTS engine. It was enriched with non-speech sounds and vibrations that were activated when the user touched pedestrian zones. Hamid and Edwards [38] presented an interactive raised-line map placed on a turntable. When rotating the turntable, users

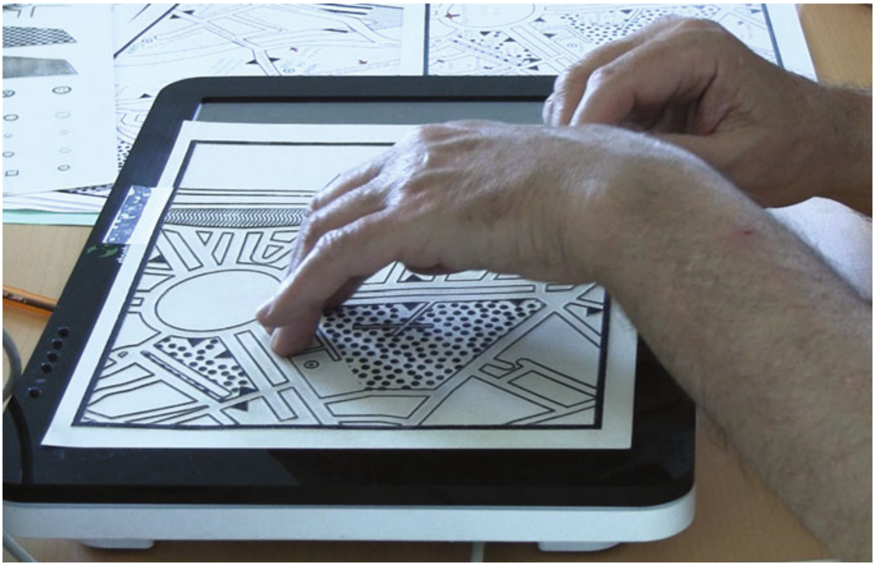

Fig. 4 Example of an Interactive Tactile Map: a raised-line map overlay is placed on top of a touch-enabled device. During exploration the device produces audio output

could explore a route from an egocentered point of view (i.e., from the traveler's perspective). In addition to the satisfaction provided by the map rotation, users reported that sounds attributed to ground textures were especially useful.

As described above, Parkes envisioned using gestural interaction in interactive raised-line maps. To our knowledge, only Brock et al. [7] implemented gestural interaction in such a map type in order to access distances between two points or to get additional information about map elements.

Mappie [9] was an extension of this previous prototype. Mappie's overlay used different colors in order to be accessible not only for blind, but also for low-vision and sighted people, which enabled them to collaborate. In addition, a menu bar was included to enable users to choose between different types of spatial content. Then, Brulé et al. [9] developped the MapSense prototype that relied on the same interactive raised-line maps, but provided 14 additional conductive tangibles. Some tangibles could be filled with scents, such as olive oil, smashed raisins, or honey, thus creating a real multisensory experience including olfactory cues.

Interactive Raised-Line Maps are used in the wild. ABAplans[5] is a project initiated by the Engineering School of Geneva (Ecole d'Ingénieurs de Genève). The device is based on a raised-line map overlay placed over a mono-touch-sensitive surface. It includes a specific map editor, and allows users to explore a city map, to find a specific place, to prepare journeys, and to learn about public transportation. It is currently distributed by the AudioTactile association. The company ViewPlus commercializes a similar device called IVEO.[6] It includes a mono-touch-sensitive surface and an editor for sketching raised-line maps and drawings. It is possible to purchase additional software that allows creating raised-line images from PDF or scanned documents using optical character recognition. In both cases, users must own the mandatory equipment to print raised-line maps.

Weir et al. [127] compared the usability of an Interactive Raised-Line Map to the usability of a Digital Interactive Map based on a touchscreen or a keyboard. The evaluation showed that the participants preferred the Interactive Raised-Line Map. A few studies also compared the usability of Interactive Raised-Line Maps to regular (non interactive) raised-line maps (see, e.g., [125]). Six blind users raised positive comments on the clarity of information that was provided. They found that the device was easy to use and helpful for pedestrian navigation. In a follow-up study, Wang et al. [126] compared an Interactive Raised-Line Map with a tactile map without any textual information. They observed that users preferred the interactive map. Furthermore, they observed that the interactive map was quicker in 64% of all cases for identifying start and end points of a route, but not for route exploration. However this comparison should be considered with precaution because users spent most of the time listening to the audio output in the interactive condition, whereas the tactile map did not contain any textual information. Brock et al. [8] compared the usability of a regular raised-line map to an Interactive

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[5] http://www.audiotactile.ch/ [last accessed June 3rd 2016].

[6] https://viewplus.com/product/iveo-hands-on-learning-system/ [last accessed June 3rd 2016].

Raised-Line Map that displayed comparable content. The evaluation included 24 blind participants that were required to explore an unknown neighborhood. The study assessed the time needed for exploration, the accuracy of the spatial learning, and the satisfaction of the users. The results showed that interactivity significantly shortened exploration time and increased user satisfaction.

While the previous studies have been done in a laboratory setting, other studies have been performed in a classroom scenario. Brulé et al. [9] conducted a formative study with the Mappie prototype over several months in a specialized education center. The results were promising and provided insights in the design of accessible interactive maps using other sensory modalities (i.e., olfaction and taste) to foster learning. They recommended using additional interactive objects to support storytelling. The MapSense prototype has also been used during two classes made by a locomotion trainer and a specialized teacher. The authors observed that the device triggered strong positive emotions and stimulated learning as well as creativity.

ITMs with a camera-based finger tracking

Interactive Raised-Line Maps usually combine a touch-enabled device with a raised-line overlay. Technically this works because touch inputs can be detected through the overlay (Fig. 5). Another way of tracking the user's fingers is to use a camera. With the Tactile Graphic Helper [28], a visually impaired user can place a tactile map on a regular table and then interact with it. The camera placed above the

Fig. 5 Example of camera-based finger tracking combined with a raised-line map. During exploration the device produces audio output

tactile drawing recognizes the layout and tracks the user's fingers. The user can point at elements and ask for information. The Tactile Graphic Helper aimed at allowing visually impaired students to discriminate tactile symbols (texture, Braille labels, etc.) without requiring the help of a sighted person.

Sullivan and Picinali [110] used another technology, the Leap Motion©, to detect pointing movements toward elements of a tactile map placed over an inclined table. The user had to perform a distinct pointing gesture to select a specific element. Two types of auditory feedback were given, either to provide users with detailed information about specific elements, or to guide them along a route. Spatial sounds were also played, as, for example, sounds of flowing water when a river was selected.

Götzelmann and Pavkovic [34] designed interactive 3-D printed maps. The production of 3-D maps was automatic so that visually impaired users could make them without assistance. Once printed, the fingers were tracked with a smartphone held above the 3-D map. The application identified the map with a printed barcode, and, in addition, helped the user to correctly hold the smartphone over the map. With the other hand, the user was free to explore the map, and received auditory feedback when pointing at elements.

Erasable Tactile Map

Recently, an interesting prototype based on 3-D printing has been designed by Swaminathan et al. [111]. LineSpace was a platform that included a movable 3-D printer head mounted over a drafting table. The system could print and erase spatial content based on vocal commands and deictic gestures. The gestures were detected by a camera tracking the markers affixed to one of the user's fingers. It provided visually impaired users with the possibility to dynamically draw and explore spatial content. Among the different applications described in the paper, one allowed users to search for real estates within a city map. Once the map was printed, the user could retrieve additional information about a particular estate. For rescaling the map or exploring a new part, the system printed a new map on a blank part of the drawing table, which enabled the user to switch back and forth between two different views. The system could also remove elements that have been previously printed using a "scraper."

2.2.2 Tangible Maps

Tangible user interfaces combine physical objects with digital data, and thus enable interaction with the digital world through the use of physical artifacts [120]. As already mentioned, we make a distinction between digital maps that are based on a tangible pointing device (see 2.1.1) and tangible maps per se. Tangible maps are made of several physical objects that represent map elements and allow bimanual exploration (Figs. 6 and 7). Users can also manipulate the tangible objects in order to (re)construct or edit the map. On the contrary, tangible pointing devices (such as

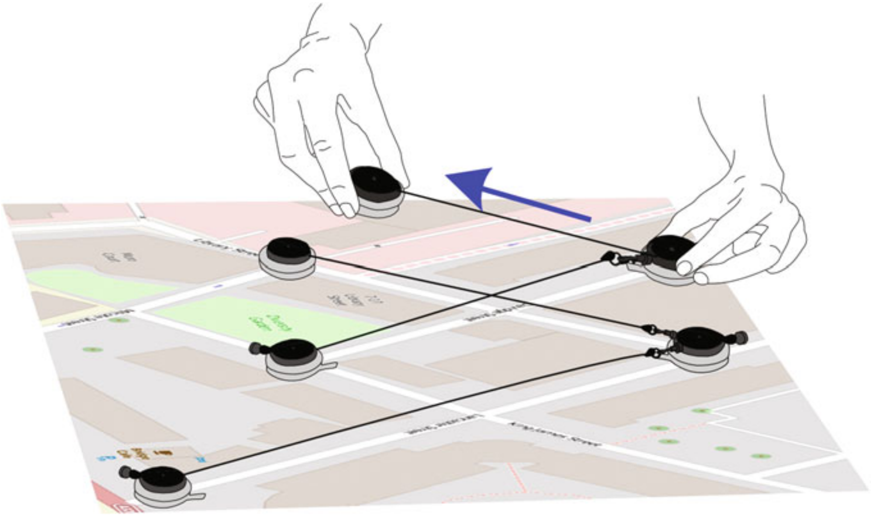

Fig. 6 Tangible Reels are composed of a sucker pad and a retractable reel and are used to construct tangible maps. The user is guided step by step to correctly place each Tangible Reel until the whole map is reconstructed. During exploration, audio feedback is provided whenever the user points at one element with one finger

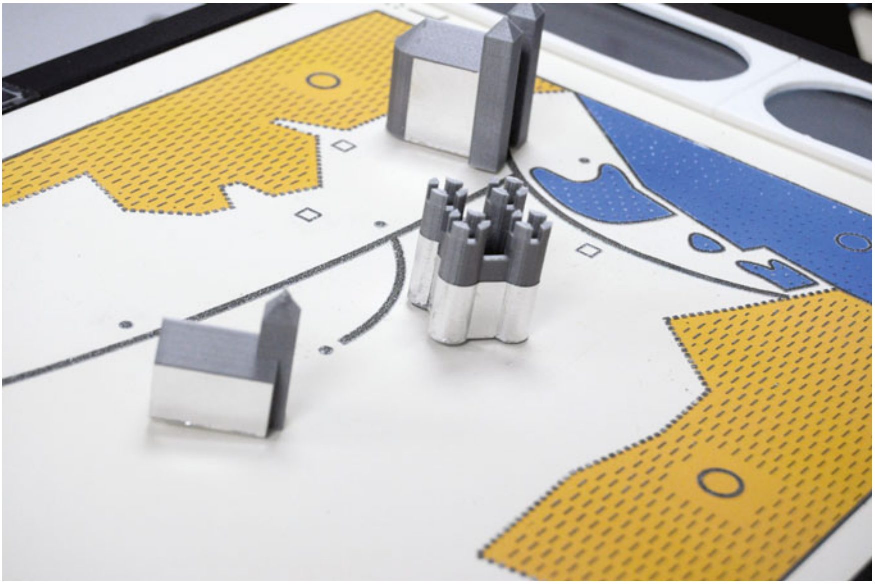

Fig. 7 MapSense combines an interactive raised-line map with additional conductive tangibles. Some tangibles can be filled with scents, such as olive oil, smashed raisins or honey, thus creating a multi-sensory experience including olfactory and gustatory cues. The Photograph is licensed under Creative Commons BY-NC-ND

computer mice, pens or toys) do not represent any element of the map but only serve as a pointing device.

Schneider and Strothotte [101] designed a prototype that enabled visually impaired students to independently construct an itinerary using building blocks of various lengths. The system indicated the length and orientation of the next building block that had to be placed. The user's dominant finger was tracked during exploration of the virtual map. More recently, Ducasse et al. [22] designed a novel type of physical icons, called Tangible Reels, which were used to render map points (cities, bus stops, etc.) and lines (streets, rivers, boundaries, etc.) tangible. The Tangible Reels were made of stable objects combined with a retractable reel. The user was guided by audio instructions to correctly place and link the objects on a tabletop, until the whole map was constructed. The user could then retrieve the name of the elements with a pointing gesture above the objects and the links. The evaluation, conducted with eight visually impaired users, showed that the interface enabled the construction and exploration of maps of various complexities (up to twelve objects), in a short amount of time (24 seconds on average to place and link an object), and with very few errors (283 out of 288 objects were correctly placed during the whole evaluation).

2.2.3 Refreshable Tactile Maps

Refreshable Tactile Maps refer to maps that are physically rendered (using a matrix of pins for example), and that the system can dynamically update. Such devices may intuitively provide blind users with access to any content, at any time. They can represent a complete drawing with different heights for the relief (also called 2.5D[7]). The display can be refreshed dynamically, and hence allows any update, as well as zooming and panning.

Raised-pin displays rely on pins that are raised mechanically either by electromagnetic technologies, piezoelectric crystals, shape memory alloys, pneumatic systems, or heat pump systems [24]. Vidal-Verdú and Hafez [123] referred to this type of devices as static refreshable displays: they are equivalent to a screen "where pixels are replaced by taxels, i.e., touch stimulation units." Visually impaired people are accustomed to this type of display because they frequently use dynamic braille displays that are based on a similar principle [5]. Braille displays are used to display textual information. They are made of one or two lines of 40–80 cells, each with 6 or 8 movable pins that represent the dots of a braille cell.

Four map prototypes have been designed using a large display composed of actuated pins. These displays present information in relief. The user moves the hand across the display to explore the content. Obviously, it is possible to dynamically

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[7] 2.5D has been defined in opposition to 2D (flat and without relief) and 3D (object). 2.1D is sometimes used to refer to relief with just one height. Braille cells are 2.1D devices because the raised pins can reach one position only.

change the content or to highlight elements by raising or recessing specific pins. Zeng and Weber [137] used the BrailleDis 9000 tablet which was composed of 7200 pins arranged in a 60 × 120 matrix, and actuated by piezoelectric cells. Touch sensors allowed the user to provide input to the system (tap or double-tap for instance). Zeng and Weber designed a tactile symbol set for displaying different types of information such as bus stops or buildings. In a second publication, they improved the tactile symbol set as well as the prototype, and introduced the ATMap prototype that enabled users to pan and zoom but also to share annotations [139]. In their study, Schmitz and Ertl [99] used the HyperBraille display[8], a commercial version of the BrailleDis 9000, to display two types of maps: detailed maps representing buildings or small outdoor areas, and overview maps retrieved from OpenStreetMap. The prototype also provided panning and zooming functionalities. When the user typed in an address or the name of a point of interest, the map was refreshed. Ivanchev et al. [46] also used the BrailleDis 9000 to present routes to visually impaired users. They compared several patterns to help the user visualize the routes by varying the thickness of the lines or making the pins blink for example. An observation made on one subject indicated that the blinking mode was efficient. Panning, zooming, layering and searching functionalities were also implemented. Shimada et al. [105] constructed a display with 3072 raised pins. In addition, this system included a scroll bar that indicated which part of the image was inside the displayed area. This device also contained touch sensors in order to track user inputs.

2.2.4 Summary and Conclusions

In this large category of Hybrid Maps, we presented map prototypes that include an interactive physical representation of the map. The most studied prototypes are undoubtedly the Interactive Raised-line Maps. They have been evaluated in many studies, and altogether, these studies show that maps combining touch devices with raised-line overlay and audio output are highly usable for acquiring spatial knowledge in absence of vision. In addition, they are now on the market and are being used in many situations like at home or at school. The downside of these devices lies in the necessity of tactile overlays, whose production is time consuming and relies on tactile document makers. In commercial offers, they are sold as packages for a region or a country. Tactile overlays also limit the usage of the device in mobility, because of physical bulkiness and weight [58]. Furthermore, zooming or panning operations are not possible without placing another tactile overlay, which may cause cognitive issues.

It is therefore interesting that some projects aimed at automatically producing tactile overlays either by retrieving spatial data from a Geographic Information Systems, or based on image recognition and segmentation. Campin et al. [14]

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[8] http://www.hyperbraille.de/?lang=en [last accessed August 21st 2013].

described a prototype that allowed the user to select a SVG map on a dedicated web site, and then to print it at home with a thermal enhancer. In the "Talking TMAP" project [74], the maps were automatically generated and could be ordered online. Wang et al. [125] implemented a system that automatically created interactive tactile maps from map images.

In the same subcategory, we placed 3-D printed maps that are interactive thanks to a camera that tracks the fingers. 3-D printers are affordable, and can be used to print small neighborhoods, but also small-scale models of buildings, objects, etc. They already spread over specialized education centers, but to our knowledge, no interactive device has already been used on the wild. Talking small-scale models are now used in many public places. They are now designed by a few companies (see, e.g., Talking Tactile Campus, Touch Graphics, Inc., USA). They rely on touch-sensitive zones (not on camera-based finger tracking) and proved useful for wayfinding. However, they are quite expensive and cannot be updated.

At the intersection between Interactive Tactile Maps and Refreshable Tactile Maps, LineSpace [111] is a research prototype that could be used to dynamically print and erase interactive maps on a drawing board. However, the time required to print a map was not indicated by the authors. It is therefore unclear whether the map could be readily updated or not. Obviously, LineSpace could be used in specific places such as specialized education centers but not in mobility.

The second subcategory of HIMs called "Tangible Maps" is promising, but there is surprisingly little work on that topic. This may be explained by the fact that Tangible Maps, although they can be relatively cheap (a webcam, a PC, and a table are enough), still require a large tabletop and several objects, which is cumbersome. Commercial interactive tabletops that identify and track tangible objects also exist (e.g., the Reactable[9]) but are expensive. One of the main advantages of Tangible Maps is that they support the autonomous construction of map, which may help the users to understand and memorize the spatial layout of the map [22]. Besides, because the map representation can be easily manipulated by the user, it is possible to "refresh" the map by moving the objects or adding and removing objects. It is therefore technically possible to rescale or reposition the map by moving the objects. In conclusion, tangible interfaces are not yet mainstream devices, and cannot be used in mobility. However, we guess that in the near future they should become more frequent in public spaces such as museums, schools, etc.

The last subcategory was called Refreshable Tactile Maps. It includes maps whose physical representation can be automatically updated, which is an outstanding advantage. However, the more advanced devices, namely raised-pin displays, are still very expensive. In 2007, Vidal-Verdu and Hafez [123] estimated that a display large enough to be explored with two hands would require more than 75,000 pins, and would approximatively cost 270,000 €. In 2012, the HyperBraille display with 60 × 120 pins was sold 50,000 €. Hence, current raised-pin displays

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[9] http://reactable.com/.

are generally small, with a low resolution [137]. However, they can be used in mobility [140], which is very important for visually impaired people.

3 Discussion

3.1 Comparison of Interactive Map Devices

As shown above, there is a large variety of devices allowing visually impaired users to explore maps. Each type of devices that we described in the previous sections presents advantages, drawbacks, and limitations. To our knowledge, the different types of devices that we presented in this chapter have not been systematically compared. We believe that doing so could help designers and researchers better identify the advantages and drawbacks of each device depending on the tasks that they intend to support, the context in which the prototype will be used, the sensory capacities of the users, etc.

At the end of the two previous sections (Summary and conclusions), we already discussed the advantages and limitations of the devices used in terms of cost, availability, and technological limitations. We also mentioned whether the prototypes could be used in mobility, and if they allow readily updating the map representation. In the following sections, we discuss the different categories in terms of content, factors impacting map comprehension, and interactivity.

3.1.1 Map Content

Maps are used to display spatial content that is made of points, lines and areas, with accompanying text. All the different types of Accessible Interactive Maps that we previously described do not provide the same opportunities to render these different elements. DIMs that are explored with a tangible artifact mainly rely on auditory feedback. It is therefore possible to render maps that are made of several landmarks or separated areas such as states, but the type, number and resolution of rendered elements is obviously limited. Even though 3-D sounds may increase the quantity and quality of auditory feedback, maps from this category are quite simple in general. In fact, most of the prototypes based on 2-D pointing devices were used to display choropleth maps, i.e., maps with regions only [6, 20, 141], or to display a limited number of landmarks [76, 90].

These limitations are very similar when the DIM is directly explored with the fingers. Finger-based exploration prevents from having reference frames issues (when the visually impaired user does not exactly know where the device is pointing) but cannot provide more complex maps. In particular, it has been observed that the simple exploration of lines is problematic [58]. For example, Poppinga et al. [93] reported that participants were not able to know whether two roads were close to each other or were crossing each other. They also had difficulties to identify the direction of short roads, and were less accurate when redrawing a “zoom-out” map than a “zoom-in” map, i.e., when more roads were displayed on the screen. Additional feedback can be provided with the vibrations of the devices, but the vibrations are not spatialized (i.e., the whole device vibrates), and hence cannot provide accurate cutaneous feedback. Consequently, most of the existing Digital Interactive Maps based on finger exploration are quite simple, and only display a very limited number of elements [57, 89, 106, 109, 131].

DIMs that are based on less conventional tactile feedback (force-feedback, latero-tactile displays, Braille mice, etc.) can be more complex or detailed. For instance campus maps, building plans, country maps with various cities and/or areas, street maps, etc., have been designed. Indeed, a number of cutaneous and haptic feedbacks can be used to render various elements such as boundaries, textures, points of interest, etc. [see 33]. Furthermore, haptic devices can help to recognize geometric properties of objects [5].

Hybrid Interactive Maps are very useful for visually impaired users because the relief or the objects used to display the map represent useful tactile cues. As we already mentioned, raised-line maps have been criticized for their low resolution when compared to visual maps but they remain the best way for displaying complex content, using different patterns of points (e.g., triangles and circles), lines (e.g., dotted lines and plain lines), and areas (filled and half-filled). When making them interactive, Braille labels can be removed, and new elements can be added [8]. Besides, the fact that they support two-handed exploration is highly beneficial [128].

When compared to Interactive Tactile Maps, Tangible Maps are more limited by the number and type of elements that they can render. Indeed, physical icons are generally relatively large, which limits the number of points of interest that can be simultaneously represented [see, e.g., 22]. Only two prototypes make it possible to represent lines using either physical bricks [101] or retractable strings [22]. Although the former prototype allowed the construction of routes only, the latter allowed the construction of complex representations. There are many advantages to physical lines: users can easily locate and identify them, but also interact with them, which can be used to provide useful pieces of information on borders, rivers, transportation routes, etc. Yet, there is still a challenge on rendering areas with Tangible Maps.

Finally, raised-pin displays are really adapted for rendering various patterns of symbols [139] and lines [46], but their resolution is drastically limited by the size of the device and the number of pins. Then, even though it is possible to display various points of interests, lines and areas, the current prototypes cannot be used to display complex maps. Besides, several pins are needed to distinguish different symbols [139], which requires a lot of space, and hence impacts map resolution. In fact, they cannot reach the complexity of raised-line maps.

3.1.2 Factors Impacting Map Comprehension

Number of points of contact

As we already mentioned, constraining the exploration of a map to a single point of contact makes the map exploration cognitively more challenging. Indeed, in order to build a mental representation of the map being explored, users must perform a complex cognitive integration along space and time. They must integrate the path of their own movement and of the movement of the cursor with a transfer function if a pointing device is used. In addition, users must integrate the tactile cues under their fingers, which are related to each position over time [58]. This complex integration process is cognitively demanding, and may impact user's performances. For example, Loomis et al. [70] showed that exploring a raised-line drawing with one finger only (i.e., one point of contact) is similar to exploring a visual drawing with a narrow field of view (the size of a fingertip). Not surprisingly, two-handed exploration of tactile images proved to be more efficient than exploration with one hand only [128].

Among DIM prototypes, only the GRAB [45] prototype, which relied on a force-feedback device with two handles, provided more than one point of contact. The evaluation showed that using a second point of contact helped users "orientate themselves in space, more readily understand object's relationships (distribution and distance) and make re-finding objects easier."

Because they rely on a physical representation of the map, HIMs allow two-handed exploration. In addition, most of them provide multiple interactive points of contacts. Among Interactive Tactile Maps, earlier prototypes (see Abaplan for instance) relied on a single interactive contact point. More recent Interactive Tactile Maps [see, e.g., 8] provide many interactive contact points, which support multiple fingers and gesture command menus. Interestingly, Brock et al. [8] observed that visually impaired users may prefer deactivating audio output when exploring a map for the first time. Finger tracking in Tangible Maps can either rely on cameras [101] or infrared frames [21]. Even though in the prototype of Schneider et al. only one finger was tracked, it is now possible to track multiple fingers using a camera. Thus, it would be interesting to design gestural interactions and evaluate their usability. As for raised-pin displays, they can detect touches and therefore offer a wide range of possibilities to interact with the map.

Haptic frame of reference

Another important aspect is the possibility offered to the user to build a reliable mental reference frame during tactile exploration. Millar et al. [75] showed that using an external (allocentred) reference frame to encode spatial information resulted in better performances.

DIMs based on keyboards and joysticks do not provide a reliable external haptic reference frame. Indeed, the displacement of the cursor is relative to the previous position, and its current position within the map cannot be inferred by touching the pointing device. Both Zhao et al. [141] and Delogu et al. [20] reported that using a keyboard made it difficult for the user to know the cursor position within the map. DIMs based on mice and handles do provide a better feedback to build a haptic reference frame, but can still generate confusions if the movement of the cursor is not directly mapped to the movement of the pointing device. DIMs based on direct exploration provide a more reliable reference frame because the mapping between the hand and the map is fixed. In addition the outline of the touch-enabled device can be perceived, which represents efficient tactile landmarks. When using a camera to track the hand instead of a touch-enabled device, these tactile cues are missing. Therefore, some prototypes included a rigid frame that delimited the exploration area [see 3].

Most of force-feedback devices also provide an external reference frame because the displacement of the device is in general constrained. The device cannot move over physical limits in space. Rice et al. [97] reported that such a frame was very helpful. However, the physical limits of the device can be used as a reference frame if they correspond to a static view of the map. If the map view is displaced when the user pushes toward one side (sometimes called "inertial displacement"), then, in absence of efficient feedback, the reference frame is lost.

Obviously, HIMs provide a very stable and reliable haptic reference frame. Indeed, any static point of the tactile display (relief, identified item, edge of the display, etc.) can serve as a reference point, and anchor the reference frame. The reference frame can then be fed by all the other static tactile elements displayed in the map.

3.1.3 Map Interactivity

Updating map content, zooming and panning

All the accessible interactive map prototypes that we described share a basic feature: the user can select a map element to retrieve its name. However, very few prototypes provided additional interactions with the map representation (e.g., panning, zooming, filtering, highlighting) or eventually the map content (e.g., annotation, edition).

DIMs can be dynamically updated and are not limited by physical constraints. In that sense, they are similar to visual maps that sighted users can access online, and share the potential of providing visually impaired users with access to a large quantity of geospatial data. However, performing zooming and panning operations on DIMs, without any tactile cue, leads to sensory and cognitive challenges that have not yet been addressed in any experimental study.

Unlike DIMs, Hybrid Interactive Maps (HIMs) are shaped and constrained by their physical representation. Interactive Tactile Maps are constrained by the tactile overlay, which cannot be dynamically altered. Different map contents, but also different views or different scales, must be rendered with different tactile overlays. Of course, it is possible to pre-print these different overlays, and dynamically call the corresponding digital content when one overlay is being used. However, when zooming or panning, users must interrupt the ongoing exploration in order to replace the overlay, and start a new exploration process after the corresponding digital content has been called. In order to link the mental representations corresponding to both maps, they have to find reference points that were on both overlays. This procedure clearly leads to cognitive challenges again. Furthermore, users cannot select a scale or a view that has not been previously prepared. At the intersection between Interactive Tactile Maps and Refreshable Maps, LineSpace (Erasable Tactile Map) did not provide regular panning and zooming operations. Instead, a new map with a different view or scale was printed over a blank space around the map being explored. However, the cognitive issues that we already mentioned (interruption of the current exploration and finding common reference points) also apply in that case.

The dynamicity of Tangible Maps is also constrained. Moving, adding or removing tangible objects is possible. Obviously, rescaling and repositioning take some time, but it renders the representation more flexible than regular tactile maps such as raised-line maps or 3-D small-scale models. Nevertheless, further studies are required to investigate whether Tangible Maps raise perceptual and cognitive issues. In the GeoSpace tangible and visual map [119] users could rotate and rescale the map by moving two objects, but only a few elements of the maps were rendered using physical objects. Shaer et al. [104] refer to this problem as a problem of *scalability:* when one user needs to zoom in or zoom out, all the objects need to be repositioned, i.e., the whole map needs to be reconstructed.

Refreshable Tactile Maps are the most dynamic interactive maps. It is possible to update the content instantly, but also to provide advanced interactive functions such as zooming and panning operations [105] or annotation [140].

Adapted exploration functions

Additional functions that help visually impaired users to explore maps are not specific to DIMs or HIMs. They can provide verbal descriptions and guidance, spatial and semantic filtering, but also specific computations (e.g., distance between two points). Some functions have been implemented and evaluated.

As we previously mentioned, it is a challenge to find and relate specific points when the exploration is tactile, especially when it is performed with only one contact point. For instance, Kane et al. [57] developed three interaction techniques to help the user locate, relocate and relate points of interest on a map. The Talking TMAP prototype [74] provided assistance to find a location, and calculate distances, but also provided a menu for modifying the settings (sensitivity, unity of measure, and speech rate).

With the Interactive Raised-Line Map called Mappie [9], children could also rely on audio instructions to locate specific points of interests. In addition, they were able to choose among different types of spatial content (city, countries, etc.) for the same overlay, which is very useful for teachers. Indeed, the same tactile overlay may be used in conjunction with different digital contents. It may then serve successive lessons of the same discipline, but also different disciplines. One tactile overlay representing a country can for instance be used for Geography lessons and the digital content can be updated as the lesson goes on. The same overlay can also be used for a lesson in Economics, with a different digital content.

Other prototypes provided access to complex functionalities. For instance, iSonic [141] included a "gist" of the map, which was a sequence of sounds that provided users with an "overview" of the regions. A subpart of the map could then be selected. The iSonic prototype provided additional functions such as: details-on-demand, adjust information level, situate (give the current status of the interface), select (only the regions selected triggered audio feedback and are played for the gist), brush (between the table and the map views), filter and search. Bardot et al. [2, 3] also implemented several interaction techniques for spatial or semantic filtering of the map content. A first one allowed the user to get a spatial overview of the map before being guided towards a specific point of interest. A second one enabled users to select the content to be displayed, and therefore avoided the cumbersome exploration of undesired items.

3.2 Geographic Maps for Visually Impaired People and Spatial Cognition

Maps serve a concrete purpose: acquiring spatial knowledge about an environment. In the following sections, we present studies on acquisition of spatial knowledge without sight that have been done using tactile maps or interactive maps.

3.2.1 Tactile Maps and Spatial Cognition

Some studies specifically investigated the benefits of tactile maps for spatial learning for visually impaired adults. Jacobson [48] compared sketch maps drawn before and after reading tactile maps. He observed that the sketch maps drawn after map reading included far more description and details than the initial sketch maps. In another study [50], visually impaired adults failed in estimating relative distances between towns, but succeeded in locating towns on a partially complete tactile map. Furthermore they successfully determined which map was correct out of a set of three rotated maps. In a follow-up study [47], sketch maps proved to be more accurate for a group of participants which had explored an audio-tactile map compared to subjects having walked the same route with a mobility instructor. Espinosa et al. [26] observed that participants who learned a route from a combination of direct experience and tactile map reading had a better spatial knowledge of the environment than those learning the route from direct experience only or verbal descriptions. In a second experiment, participants performed just as well after exploring a tactile map as after direct experience in the environment. Similarly, Caddeo et al. [13] observed that participants who had access to a tactile map showed better performance in walking time and a reduced deviation from the route as compared to participants directly experiencing the environment with or without verbal descriptions. Similar results have been found, when studying tactile maps with visually impaired children [122].

Different hypothesis explain why tactile maps are well adapted for acquiring spatial knowledge in the absence of vision. Tactile maps preserve relations between landmarks in space but present those relationships within one or two hand-spans [121]. Thinus-Blanc and Gaunet [116] argue therefore that the exploration of a tactile map demands a smaller working load than the exploration of a real environment. Also they outline that during tactile exploration of space, it is possible to keep a fixed reference point, whereas during the exploration of space via locomotion, the participant is moving and so is the reference system (the own body). Besides, the tactile map is simplified in content and therefore free from the perturbations that can be present in the environment [121].

3.2.2 Interactive Maps and Spatial Cognition

Several studies investigated if interactive maps can be used for acquiring spatial knowledge by visually impaired people. Very often these studies compared different groups of users including early and late blind, but also people with residual visual perceptions, and blindfolded sighted.

First we report the studies that have been done with blindfolded sighted people, and which may present limited validity due to the perceptual and cognitive differences between visually impaired and sighted people. Poppinga et al. [93] asked eight sighted users to explore a smartphone application with vibration and audio output and to draw a map of the perceived environment. They compared two zoom levels and observed that the “zoom in” condition resulted in a more accurate drawing than “zoom out” condition. Participants correctly perceived basic information concerning the map, but also relations between map elements. However, the authors suggested that the task was cognitively demanding as participants needed up to 15 min for sketching a rather small map. In another study [68], 24 blindfolded sighted subjects compared two conditions of a DIM prototype with speech output. In the first condition only names of landmarks and routes were indicated. In the second condition, additional information about the relationships between geographic items was provided. Participants acquired more precise spatial knowledge in the second condition. However, the result also depended on the type of spatial knowledge. Scores related to landmarks showed a larger difference between the two conditions than scores related to routes. Pielot et al. [88] evaluated a DIM with a tangible pointing device with eight blindfolded sighted participants. The results showed that the tangible pointing device, called a virtual listener, allowed detecting small deviations from the real orientation. Milne et al. [76] compared two prototypes of a DIM with five blindfolded sighted participants. One device was based on a stylus while the other was based on body rotation. They observed issues related to the shifting of reference frames between egocentred and allocentred perspectives.

Other studies were done with blind participants and therefore present a higher validity. Among these studies, a few evaluated DIMs are based on touchscreen devices and audio output. Jacobson [47] asked five visually impaired and five blind people to evaluate a map prototype based on a touchpad with auditory feedback. He analyzed verbal descriptions, map drawings, and qualitative feedback. He observed that all users successfully created mental representations following the DIM exploration. Besides, the users found the interface simple, satisfying and fun. In the study of Heuten et al. [42], eleven blind users explored a DIM based on a touchpad and a stylus, with the instruction of understanding spatial relationships between map elements. Users found the exploration easy, except for the identification of the shapes of the elements. The authors also observed confusions when two similar objects were close to each other. Yairi et al. [132] asked four blind people to explore a DIM with musical feedback, and then walk the route unaided. All participants reached the goal, even if one was unsure about it. Even if people made wrong turns at cross points or felt lost, they were able to correct their route. Simonnet et al. [107] observed two blind sailors learning a maritime environment with a haptic device and then navigate at sea. Their study revealed that using the map was beneficial because the users had to mentally coordinate egocentred and allocentred maps. In a more recent study, Picinali et al. [87] compared the results of five blind participants who walked along a corridor versus five blind participants who explored the DIM with a joystick. The results showed that all participants were able to build correct mental representations that were similar to the reference map. All these studies show that DIMs with audio output can effectively be used for creating mental maps.

As we mentioned, DIMs can be augmented with vibrations. In the study of Simonnet et al. [106], one blind user explored a DIM based on a tablet with auditory and vibratory feedback. After exploration, the user had to draw a map of the explored environment. They observed that the drawing was relatively precise. In the study of Yatani et al. [133], ten blind and two low-vision participants explored a DIM based on a smartphone with audio and vibratory output, but in two different conditions. In the first condition, the subjects used the smartphone with auditory output only. They received additional vibratory feedback through nine motors in the second condition. They were then asked to draw the maps. The drawings were more accurate with additional tactile feedback.

A few studies investigated the acquisition of spatial knowledge with HIMs. Jacobson [49] compared route learning with a mobility instructor versus with an Interactive Tactile Map (touchscreen with tactile overlay). The author used many methods including verbal description, map drawing, distances by ratio-scaling, tactile scanning assessment, and talk aloud protocol. The results showed that both groups were able to complete the route and verbally describe it. All sketches showed a high degree of completion and correctness but the group who had explored the interactive map was more accurate. Participants also provided positive qualitative feedback. More recently, in a study with 24 blind participants, Brock et al. [8] compared the usability of an Interactive Tactile Map versus a regular raised-line map with braille legend. They measured the time required to explore the maps, the correctness of the spatial knowledge acquired during exploration, and the satisfaction. The results showed that Interactive Tactile Map was significantly more efficient, and preferred among users.

Finally, Zeng and Weber [136] evaluated the acquisition of spatial knowledge using a Refreshable Map with ten blind users. They compared it to two other conditions including a regular raised-line map, and a DIM displayed on a tablet. They measured the subjects' performances in reading street names and preparing a journey. The results showed that participants were able to perform these tasks using the raised-pin device or the raised-line map, but failed to perform them on the tablet.

In conclusion, it appears that DIMs can be used to acquire spatial knowledge but, except in the study of Yairi et al. [132], spatial learning was limited to simple topological features (relative positions of items within the map).

In some of these studies, but also in the literature in psychology, there have been contradictory results showing that early blind, late blind, visually impaired, and sighted subjects outperform each other [17]. Other factors, including expertise in tactile reading, education level, but also the type of drawing being read, might have been confounded with the visual status. In any case, we suggest that a greater access to interactive maps is mandatory for visually impaired users and will decrease the differences between the different groups of subjects.

3.3 Maps and Other Graphics

The challenges related to the accessibility of maps for visually impaired people are similar to those observed when designing accessible interfaces for other types of interactive graphics. By graphics, we refer to a variety of materials whose layout is used to provide spatial content to the reader including diagrams, figures, drawings, as well as maps [115]. In this section, we present a non-exhaustive list of Interactive Graphics prototypes. They illustrate how interactive devices providing non-visual access to maps and graphics are similar. As for maps, it is easy to classify the Interactive Graphics prototypes in two categories (Digital and Hybrid Interactive Graphics, which we call DIGs and HIGs) and their subcategories.

3.3.1 Examples of Interactive Graphics

A number of DIG prototypes were based on touch-sensitive surfaces or motion capture. For example, the AudioFunctions prototype combined a novel sonification technique with touch interaction to enable a visually impaired person to explore a mathematical function [113]. Users performed better using the prototype than using a raised-line diagram. Other prototypes [30, 134] enabled visually impaired users to identify simple shapes displayed on a touchscreen device. TouchMelody [95] augmented raised-line diagrams with spatial non-speech sounds. Both the index of the non-dominant hand (used as a reference point) and the index of the dominant hand (used to explore the diagram) were tracked by a motion capture system, and a sound was played according to the position of one index as compared to the other one.

Force-feedback devices have also been used. The prototype designed by Yu and Brewster [135] could be used with either a Geomagic Touch X device or a Logitech WingMan Force-Feedback mouse, and enabled visually impaired users to explore line graphs or bar charts. McGookin and Brewster [72] designed a prototype that enabled users to drag the bar of a bar chart. Bernareggi et al. [4] developed a system that enabled users to insert, delete, connect or disconnect nodes.

Giudice et al. [32] combined gestural input with audio and vibratory feedbacks. When users moved a finger over the tablet, vibratory patterns indicated whether they were touching edges or vertices. This prototype proved efficient for the exploration and understanding of bar charts as well as for letter recognition tasks and orientation discrimination tasks.

Pointers with additional tactile feedback have been used in other prototypes. Wall and Brewster [124] used a stylus for pointing combined with a mice with an array of pins (VTPlayer). The user pointed to different zones of the graphs, and received tactile cues according to the section of the pie chart being explored. Pietrzak et al. [92] used a similar device to provide directional cues that guided the users during the exploration of geometrical shapes. Levesque et al. [65] showed that simple and small shapes could be rendered using the STRESS latero-tactile display and three primitive drawings (dots, vibration and gratings).

Examples of HIGs include the tangible prototype for the non-visual exploration of graphs by McGookin et al. [73]. This system combined a fixed grid and movable objects that represented the top of a bar or the turning point of a linear function. When moving a slider along the x-axis, the user was able to retrieve the corresponding y-values, which were sonified. Similarly, TIMMs [71] were objects that provided multimodal feedback and enabled blind persons to create and modify graphs and diagrams.

3.3.2 Maps and Graphics: A Comparison

As previously mentioned, raised-line maps are bulky, not interactive, but their accessibility can be improved by making them interactive and dynamic. The same applies to any type of raised-line graphics. So far, most research projects have either focused on graphics or on maps. Obviously, researchers could benefit from taking into account both of these application areas. Yet, it remains to be explored to what extent the issues raised by interactive maps are similar to those raised by interactive graphics.

One essential point is that all graphics, whether they are drawings, maps, bar charts, diagrams, etc., are solely made of four primitives: dots, lines, areas, and labels. Moreover, colors and textures are often used in order to improve readability. Graf [36] distinguished the propositional representation (verbal annotations) from the spatial representation (the map itself that represents the topology of the environment). Considering multiple dimensions (including layout, complexity, dynamicity and usages), we did not find any significant difference between the properties of these two representations related either to diagrams or maps. Therefore no matter the field of application, findings concerning the legibility of the symbols and representations with a particular content or representation could apply to any other content or representation. For example, we cited a few articles that aimed at understanding how simple geometrical drawings that are displayed on a touch-screen could be identified using audio and vibrational feedbacks [e.g., 32, 65]. These findings could inform the design of both interactive maps and graphics prototypes. Obviously, we would need to perform comparative experiments in order to ensure that, except slight differences in complexity, there are no specific needs according to the type of graphics that is rendered.

3.4 Ongoing and Future Research in Interactive Tactile Graphics

There are a few topics that we wanted to address which represent current challenges for research in accessible interactive graphics.

3.4.1 Rich Open and Volunteered Data

In this chapter we have mainly discussed the design of accessible interactive map prototypes. Yet, for the usability of maps, the availability and reliability of geographic content is as important as the design of the devices. Indeed map prototypes will not be used outside of research laboratories if adapted geographic data is not available. In Sect. 2.2.4, we presented a few projects that aim at automating the production of adapted content or at facilitating the collection of volunteered geographic data. We suggest that OpenStreetMap is particularly relevant as specific accessibility tags such as tactile paving can be added, [25]. Then, visually impaired users, but also sighted users that want to participate, can create annotations when they are traveling or exploring the map [44, 96]. Sighted users can also volunteer to add details based on street view images [39] or on their own knowledge of the places.

3.4.2 Authoring Tools and Content Sharing

Rich and adapted open data is not the only challenge. Up to now, the automatic production of maps is still difficult and the intervention of professionals is required (see 1.1). Besides, authoring tools are not common and that they are mainly circumscribed to research projects. Researchers should closely work with tactile graphic specialists in order to better understand how the production of adapted content could be further automated. Authoring tools may then include adaptation functions that help experts but also non experts to create accessible content that is adapted to be displayed on DIMs or HIMs. Such tools may encourage professionals to create and share accessible map content. Successful projects have been developed [34, 53, 54] and should now be tested in the field, to evaluate their long-term impact upon the accessibility of graphical data for visually impaired users.

3.4.3 Shape-Changing Interfaces

Interactive Tactile Maps present a high usability because they provide reliable tactile cues and ahaptic reference frame, as well as interactivity. However, they are constrained by the physical overlay, which prevents dynamic zooming and panning. In contrast, refreshable displays, which include both physical and digital representations, offer remarkable possibilities for dynamic interaction with maps and graphics (including, zooming, panning, annotation, filtering, etc.). In addition, they enable users to explore the maps with both hands, which is more efficient. However, those devices are currently very expensive, which prevents a large adoption by visually impaired users and professionals. Moreover, current prototypes only provide a small surface size.

Low-cost and large refreshable displays are still at infancy, but a number of approaches are promising. Shape memory alloy actuators change shape when they are heated. Voice-coil motors and piezoelectric actuators may also provide solutions for larger displays [see 80, 123 for reviews]. Wilhelm et al. [130] developed a prototype based on microfluidic phase change actuators. The actuators are filled with a phase change material that can be heated. When pressure is applied, the membrane laid over the display bulges. Taher et al. [112] investigated new interactions with physical bar charts. Other research works have to be mentioned, such as Relief [64], inFORM [27], and Lumen [94]. These physical visualization devices could increase the accessibility of graphics for visually impaired users in the future.

3.4.4 3-D Printing with Embedded Interactivity

There are several limitations to 3-D printing such as the relatively high cost for acquiring a printer, time for printing, limited size of the printed object, and lack of interactivity once printed. However, it is an emerging tool for the production of maps, graphics, and books for visually impaired users. We already described the work of Götzelmann and Winkler [35] who automated the production of interactive 3-D maps, which in contrast to raised-line maps can provide multiple levels of relief. Many other recent studies show the importance of 3-D printing for visually impaired users.

Buehler et al. [10] reported that the creation of educational materials is one of the three primary functions of 3-D printing in special education. With 3-D printing, it is possible to print customized objects that can be used to explore or annotate maps.

For example, users can explore a virtual map by moving and rotating a toy above a table [88]. Such a toy could be personalized using 3-D printing in order to get the students more engaged with the exploration task. Brulé et al. [9] used 3-D printing to create tangible objects that could be used in association with an Interactive Tactile Map device. Such objects could be placed on a tactile map to augment the information that is displayed or to highlight important elements. Giraud and Jouffrais [31] showed that 3-D printing with low-cost prototyping resources empowers specialized teachers to create their own teaching material. Swaminathan et al. [111] proposed a sense-making platform for blind people using dynamic 3-D printing. Finally, Gual et al. [37] compared the use of 3-D printed symbols versus 2-D tactile symbols in a tactile map. They found that 3-D symbols were easier to memorize than 2-D symbols.

Recent work has also shown that 3-D printed objects are not limited to non interactive plastic structures. Current 3-D printers can print soft and interactive objects that embed conductive filaments [85]. Objects produced with those printers could greatly enhance the interactivity of Tactile Maps and Graphics as they could potentially vibrate, move, emit sounds, or detect how they are grabbed.

4 Conclusion

In this chapter we presented an overview of accessible interactive maps for visually impaired people. We identified two families of Interactive Maps that differ according to the presence or absence of a physical representation of the map, which is useful for visually impaired users because it is perceivable by touch. The first family was called Digital Interactive Maps (DIMs) and relies on a digital representation of the map only. The second family was called Hybrid interactive Maps (HIMs) and relies on both digital and physical representations of the map. We defined subcategories in each family that, hopefully, may help to structure the research field.

In each family, we have observed a large variety of prototypes based on various input and output interaction devices. They have leveraged the design of non-visual interaction techniques allowing visually impaired users to explore a map. Additional functions have been designed too, allowing zooming, panning, annotating, sharing, visualizing over time, etc.

However, these different devices come with advantages and shortcomings. DIMs based on pointing devices such as touch-enabled screens or video tracking are available at low prices and thus affordable for everyone. They can easily be used in many situations (home, school, mobility, etc.) but they miss tactile cues that are useful for non-visual exploration because they facilitate haptic integration, and also provide a reliable haptic reference frame. Hence they must be designed for specific conditions such as mobility, and for compensating the absence of tactile cues. In addition, spatial content should not be too complex.

Based on a physical representation, HIMs are more adapted to non-visual exploration. We observed that one type of HIM—Interactive Raised-Line Maps—has been largely addressed in the literature (design and evaluation). Because they have a high usability, they are now spreading in the wild, and devices are being used in specialized education centers. Of course, they still suffer from the necessity of printing raised-line maps in advance, which is manageable but costs time and money. Refreshable displays supposedly provide an alternative; however, they are not yet available with a sufficient resolution at affordable cost. Tangible Maps have not been extensively studied so far. With the spreading of TUIs, but also 3-D printers and low-cost prototyping technologies, we predict that, during the upcoming years, these devices will get further addressed as a research question, but also more used in the wild. Indeed, although spatial resolution will always be limited by the size of the physical icons, they provide an appropriate setup to explore and manipulate spatial data without vision, especially in collaboration with other sighted or non-sighted users.

We have to mention that, nowadays, it is still difficult for visually impaired people to access geographic information. Yet, non-visual access to geographic information is crucial for education, as well as mobility and orientation. It has significant consequences on personal and professional occupations, and on social participation. Therefore, it is very important that future research work on maps focuses on the design and evaluation of novel interaction techniques, but also on devices that are readily usable. As an agenda for short- and mid-term research, we suggest topics that should be addressed: improving the accessibility of Digital Maps with wearable technologies; facilitating the autonomous (without the intervention of a tactile document maker) making of Interactive Maps; and designing interaction techniques that provide visually impaired people with more interactive functions such as zooming, panning, annotating, and collaborating. Obviously, researchers and designers should always keep in mind that maps serve a purpose: the acquisition of spatial knowledge. In order to validate that the devices effectively serve this purpose it is necessary to conduct user studies with visually impaired users. When possible, new displays should be studied in situ, i.e., outside the lab, to better understand how and why interactive maps and graphics are used.

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Smart Multisensor Strategies for Indoor Localization

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1 Introduction

On the tail of the continuous growing of enabling Information and Communication Technologies (ICT), including sensors, electronics and signal processing, researchers are strongly involved in the development of assistive systems to improve the life quality of frail people, thus facing the "Society for All" challenge [1–7]. This is really becoming a societal challenge which involves efforts from the industries, research centers and the European Commission.

The World Health Organization (WHO) is focusing on the problem of disability. Blindness is one of the most invalidating form of disability which involves hundreds of millions of people all over the world. Although blind people can express a high level of autonomy in performing both indoor and outdoor activities, very often unfamiliar environments can cause discouragement, loss of self-confidence as well as can compromise their social inclusion and job opportunities. Structural, psychological and cultural barriers make things even more complicate.

Thinking to the Society for All, including people with impairments, means providing efforts for bringing technologies to all, making services available and exploitable to all, making environments comfortable for all. ICT technologies can dramatically help such development, with the aim to adapt the society to frail people needs, rather than asking them to fit the society requirements.

Exploiting technologies already available and distributed in the environment, as well as enriching everyday environments with new sensing capability, could be the right solution to promote such form of technological driven inclusion.

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Assistive solutions must be "User Centered Designed (UCD)" to improve and to encourage the user acceptability and confidence in the use of such devices. The UCD concept involves many different aspects, such as reliability, the form, quantity and meaning of the information these devices are able to provide the user with, needs of demanding training, cosmetics, costs. These aspects are well covered in the literature and will not be addressed through this work.

Among primary needs of blind people, indoor and outdoor navigation remains a critical task, both from a technological and a social point of view. Independent travel is an important goal sought by most visually impaired and blind people.

It is interesting to observe that studies have demonstrated that the most important traveling aids for the visually impaired person are still the white cane and the guide dog. They are multifunctional, reliable and also tell others that the person is visually impaired.

Such thought can lead to the consideration that the main target of electronic aids should be not replacing primary traveling aids, but to develop complementary systems (to be used along with the cane or the dog) which are reliable, efficient, easy to use and to wear and providing an optimized redundancy of information.

In the following Section a review of assistive technologies aimed to improve efficiency in performing mobility tasks in indoor environment is presented. Section 3 is dedicated to discuss, as a case of study, an active and assistive system aimed to provide blind users with useful information for a safe and an efficient exploitation of indoor environments.

2 Related Works

Extensive reviews of assistive solutions for people with sensory disability, such as blind, are available in the literature, which highlight the strategic role of enabling technologies in improving their functionalities [1–7]. In the framework of systems assisting users during their mobility, two main classes of devices can be identified: Obstacle Detectors and Location Bases Services (LBS).

Several technologies have been exploited to develop obstacle detectors, including ultrasonic, infrared, laser and cameras. Some of these devices use auditory and/or tactile technology to provide the user with a useful piece of information [8, 9], as well as electromagnetic and optical technologies [10, 11]. Approaches based on vision systems, which convey the achieved information to the user by sound or tactile interfaces, are presented in [12, 13].

Navigation systems based on Location Based Services for indoor environments should be able to build awareness of the user/environment interaction, in order to provide the user itself with strategic information for a safe and efficient exploitation of that area. To such aim very accurate localization systems are required.

Localization systems using digital tags, active badges, infrared or ultrasound devices and photodiodes to transmit some form of remote signal once the user gets into the range of the device, suffer from the discontinuous information provided to the user as well as installation costs and complexity. On the other side, solutions based on inertial sensors suffer from cumulative position error and drift [4–6].

More efficient strategies adopt real time and continuous localization systems, based on Vision, InfraRed (IR), UltraSounds (US), WLAN, Wi-Fi and Bluetooth enabling technologies. In the following main approaches are briefly presented, with reference to outstanding reviews in the field [14, 15].

In [14] the state of the art in methodologies for indoor localization is presented, with particular regards to Angle of Arrival (AoA), Time of Arrival (ToA) and Fingerprint techniques, highlighting advantages and drawbacks of each approach.

A benchmark between different technologies and localization systems is provided in [15], mainly in terms of accuracy, costs and complexity.

Vision based systems are based on the matching between previously recorded images with the captured one or on real time target tracking [16, 17]. Interesting solutions exploiting IR technology can be found in [18–21]. US based indoor localization systems, exploiting trilateration paradigms, are presented in [4, 15].

Performances of WLAN based localization systems relying on the use of RSS, Triangulation and Fingerprint are addressed in [22, 23], respectively.

Above statements allow to affirm that indoor localization systems can be classified on the basis of different key factors, at different levels: the measurement strategy (TOA, AOA, RSS), the adopted enabling technology (vision, US, IR, Wi-Fi), the localization algorithm (trilateration, triangulation) and applications. Being above mentioned approaches just some examples among solutions available in the wide panorama of indoor localization strategies.

Drawbacks of localization systems can arise from high/medium costs of the adopted equipment (vision and IR), multipath issue (IR and sometimes US), Non-Line of Sight (NLOS) (vision, IR, US), installation requirements (IR, US), low accuracy (Wi-Fi), power consumption (vision, Wi-Fi).

Table 1 provides some examples of Enabling Technologies for indoor localization, along with some specifications and main drawbacks.

Table 1 Benchmark between Enabling Technologies for indoor localization

Technology	Advantages	Drawbacks	Accuracy (m)	Operating range (m)
Vision and image processing	High accuracy	High cost NLOS	10^{-3}–10^{-1}	1–10
US and trilateration	High accuracy Low cost	Installation requirements NLOS	10^{-2}	1–5
IR and triangulation	High accuracy Low cost	Installation requirements NLOS	10^{-2}	1–10
WLAN (RSS, fingerprint)	Low cost No installation requirements LOS not required	Low accuracy	1–20	10–50
Bluetooth	Low cost LOS not required	Low accuracy High latency	2–3	1–30

As evidenced by the above analysis of the state of the art, the choice of the suitable localization methodology is strictly dependent on requirements coming from the specific application.

Many application contexts may require advanced indoor localization strategies, from logistics, environmental monitoring, structural monitoring, healthcare as well as Active and Assisted Living (AAL) for frail people.

In particular, in case the active assistance of frail people is pursued, the need for very accurate indoor positioning solutions emerges, fulfilling also user acceptability requirement.

In the following, a case study of a solution developed to assist blind people during their mobility in indoor environments is presented. The system uses a multi-trilateration ultrasound based systems and smart signal processing to improve the accuracy of the localization task [4].

3 A Case of Study: An Active System to Assist Blind People in Indoor Environment

As mentioned the implementation of a reliable and efficient solution to assist frail people in indoor environments requires an accurate localization system. Among the enabling technologies, ultrasound based localization systems assume a strategic role for the very high accuracy which can be reached, at the expense of a sensor network which must be installed in the environment.

In the following, the implementation of a ultrasound based localization architecture is addressed, with a specific focus on the case of study of an active system adopted to provide blind users with a continuous and reliable form of information for a safe exploitation of indoor environments [4].

The system exploits emerging technologies such as Wireless Sensor Network and advanced signal processing, to get awareness of the user position inside the environment, the user and environment status, as well as the User Environment Interaction (UEI) and the User-Environment-Contextualization (UEC).

Adopted technologies and sensing methodologies allow for providing the user with a real time and continuous assistance with a high spatial resolution.

This feature, which represents a dramatic advance with respect to the state of the art, is mainly due to the performances of UEI/UEC tool and the indoor localization strategy, which shows an accuracy better than 4 cm.

In the following, the system architecture is presented along with smart paradigms adopted for the sake of user localization.

3.1 The Assistive System Architecture

The architecture of the active system developed to assist blind people while performing daily activities in indoor environments is shown in Fig. 1. The system exploits multi-sensor nodes (environment nodes and the user node) in a Wireless Network configuration. Environment nodes are equipped with sensors (for Liquid Propane Gas, Smoke and Temperature detection) and ultrasound sensors to implement the user localization task. Users are required to wear a "user node", which embeds inertial sensors for his/her status monitoring and the ultrasound sensor. The latter is coupled to the ultrasound receiver embedded in the environment nodes to implement the user localization functionality by a smart trilateration approach.

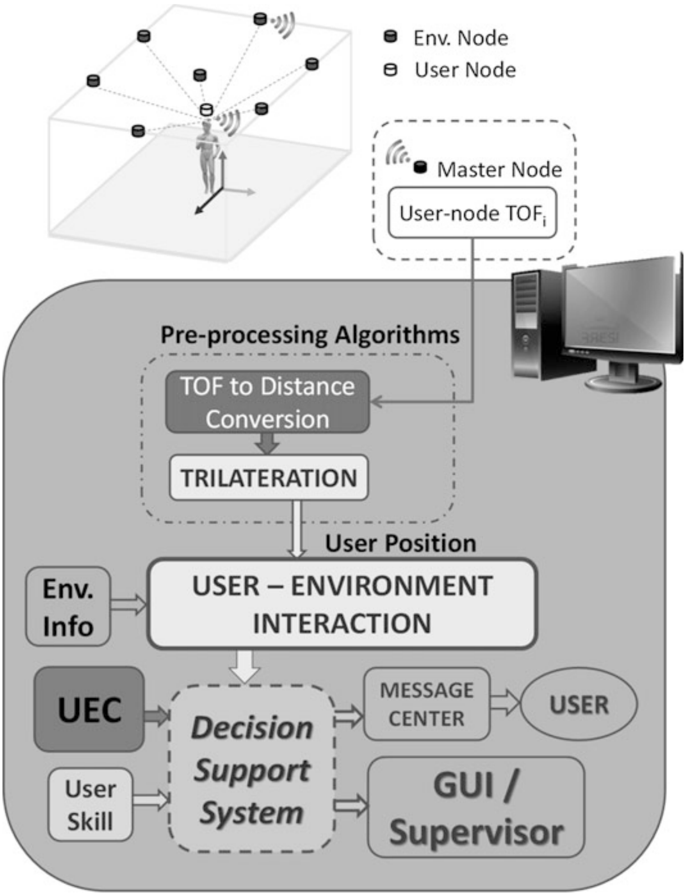

Fig. 1 Schematization of the indoor localization and assistive system (© [2014] IEEE)

Data coming from the sensor network are collected by a PC running dedicated signal processing algorithms, with specific regards to the UEI and UEC functionalities. It must be observed that the PC can be replaced by extending the computational functionality in the sensor network nodes.

The UEI is in charge of detecting events (such as collisions with obstacles or availability of services) by exploiting information on the user position and the presence of obstacle or services within the environment. As a consequence of such findings candidate messages for the user will be generated by the UEI tool. The UEC tool combines the awareness of the user inertial status (e.g. posture) as respect to the environment status (fires, gas leakage, smoke), to provide useful information to the system supervisor and to generate candidate messages for the user. Messages generated by these tools have a well defined degree of priority which will be managed by the Decision Support System (DSS) service, in order to properly deliver messages to the user with an optimized degree of information. The message center is in charge of delivering notifications by the user interface, implemented through a Bluetooth audio feedback device. The supervisor can get awareness of the user interaction and contextualization within the environment by exploiting the information provided by the DSS, in order to manage alert situations.

3.2 The Smart Trilateration Algorithm

The ultrasound localization system is based on the continuous measurement of distances between the user and the environment nodes, d_i, which are successively processed by a smart trilateration algorithm. This approach allows for a real time and very accurate estimation of the user's position within the environment. In order the perform the estimation of d_i distance, the ToA approach, shown in Fig. 2, is used. The aim of the Anti-Bouncing Filter (ABF) is the reduction of bouncing effects in the estimation of ToAs, by measuring and processing 4 successive ultrasound impulses. The resulting ToAs are then converted in distances and conveyed to the Multi-Trilateration Algorithm (MTA) for the sake of user localization. The algorithm estimates the user coordinates taking into account and manipulating all possible combinations of d_i distances, as schematized in Fig. 3 [4, 24]. In order to produce all candidate estimations of the user position, each combination of two user/node distances is considered. Such estimations are then statistically analyzed to extract the optimal user position within the environment.

Although the MTA is higher time-demanding as respect to the traditional Trilateration Algorithm, the tradeoff between localization performances and processing time, definitively encourages its use in case extremely accurate indoor localization tasks are required [24].

Figure 4 shows an example of a path reconstruction performed by using the ultrasound/MTA localization strategy above described. As already mentioned, the localization accuracy is in the order of 4 cm. The system performances have been

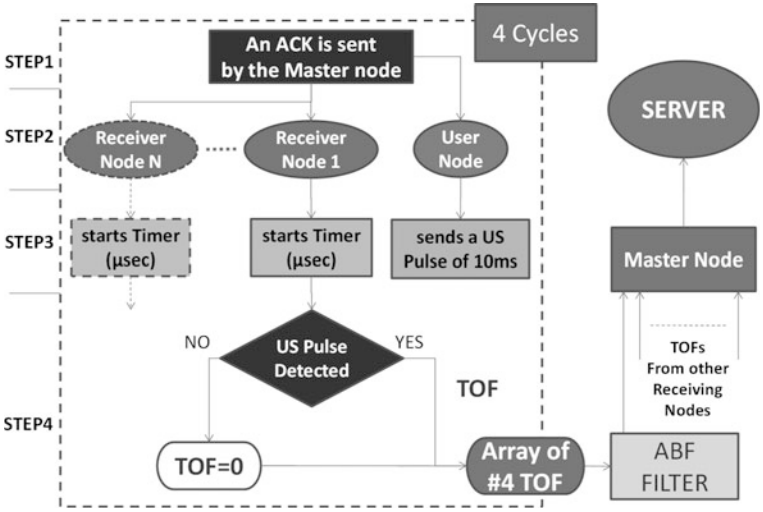

Fig. 2 Schematization of Time of Flight estimation methodology (© [2014] IEEE)

estimated by computing the index, J, weighting the residual between the estimated path (WD_{Estim}) travelled by the user and the nominal one (WD_{Nom}),over a total length of 110 m.

$$J_{\%} = \frac{|WD_{\mathrm{Estim}} - WD_{\mathrm{Nom}}|}{WD_{\mathrm{Nom}}} \cdot 100 \tag{1}$$

3.3 Compensating for Uncertainty in WSN Node Position

Sometimes, coordinates of the WSN nodes cannot be properly known due to the absence of absolute reference, irregular floor or roof height. This lack of information can increase the overall uncertainty in the estimation of the user's position. In the following, a method to compensate for node mispositioning is described, in few notes [4].

The proposed approach exploits a Nelder–Mead nonlinear simplex paradigm for the optimal estimation of the node coordinates. In particular, the task of the paradigm is to find the sensor nodes coordinates which minimize the distances, h_i, between N nominal user positions and their estimations performed by the trilateration algorithm. The minimization procedure uses a rough estimation of the node position as initial conditions and the following performance index:

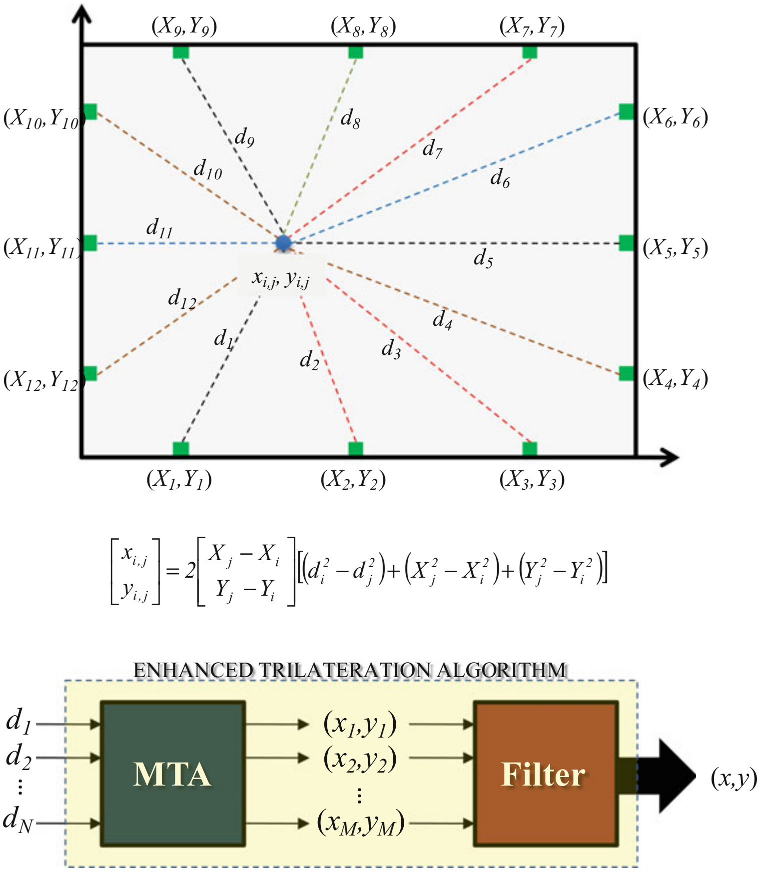

Fig. 3 Schematization of environment to implement the trilateration paradigm. Coordinates of the user in the plane, $(x_{i,j}, y_{i,j})$ are estimated by each pair of environment sensor nodes (X_i, Y_i) and (X_j, Y_j) (© [2011] IEEE)

$$J_{\mathrm{ED}} = \frac{\sqrt{\sum_{i=1}^{N} (h_i)^2}}{N} \tag{2}$$

During the minimization process, constraints have been imposed to limit the nodes' positions within a tolerance of ±5 cm as respect to rough measured values.

In order to assess performances of the proposed compensation method, tests have been performed in an environment of 8.60 m by 7.10 m, with seven nodes roughly positioned at a height of about 3.0 m.

For the experiment under consideration, 45 reference positions have been defined inside the environment under test, in order generate the data set to be adopted by the minimization paradigm [4]. The distance between grid points is

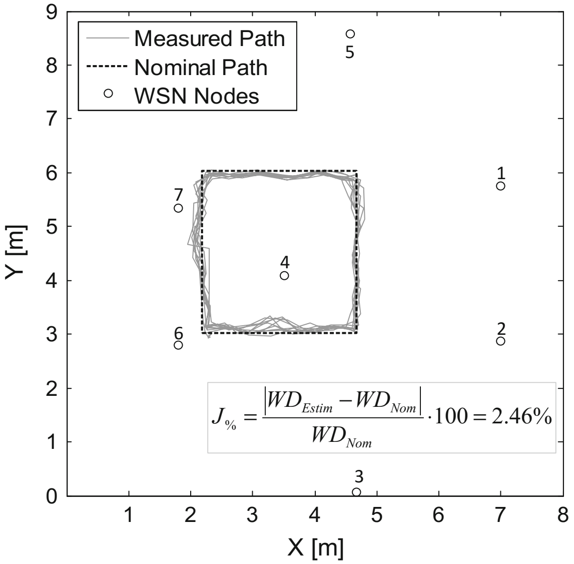

Fig. 4 Results of the tracking test by the MTA algorithm for a close walking path of 110 m (© [2014] IEEE)

0.50 m. Values of J_{ED}, before and after applying the minimization algorithm, are 6.1 and 3.9 cm, respectively, thus confirming the suitability of the proposed strategy.

4 Conclusions

A deep analysis of the state of the art confirms the strong interest in developing efficient solutions in the framework of Active and Ambient Assisted Living.

This chapter aims to provide some points of thought on active and assistive systems, with specific regards to blind people. In particular, the need for a very accurate indoor localization system is discussed against the application context to be addressed.

A benchmark between different localization strategies is presented in terms of sensing methodologies, enabling technologies and applications.

In order to properly contextualize the subject in the field of assistive systems for the visually impaired, a case of study of an active system developed to assist users performing daily activities in indoor environments is presented. The system is a valuable example of the synergic cooperation between hardware architectures and smart algorithms. The latter are mandatory to get awareness of the user status in the environment, as well as the User Environment Interaction and Contextualization. To such aim an accurate indoor localization system is developed, which exploits a ultrasound sensing strategy and MTA. The system is able to provide the user with a real time and continuous form of assistance mainly due to the real time and high spatial resolution features of the localization tool.

Finally, a method for compensating the mispositioning of environment nodes has been also discussed.

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Constructing Tactile Languages for Situational Awareness Assistance of Visually Impaired People

Ramiro Velázquez and Edwige Pissaloux

1 Introduction

Auditory and tactile channels are often used to convey information to people with visual impairments. Considering that hearing becomes the primary sense for this population and that it is generally loaded with plenty of stimuli from the environment, the use of touch has been long studied to transmit information that unloads audition and that could assist in daily tasks such as reading, computer access, and mobility [1–3].

Tactile information displayed by assistive devices normally consists of very simple tactile cues to alert of events (for example, obstacles in the immediate location or to point users to a navigational direction). However, situational awareness assistance cannot be provided as simple event alerts. In fact, providing feedback on environmental elements with respect to time or space and the update of their status after some variable has changed definitively needs a more complex communication structure such as language. It still remains a challenge for assistive devices to provide situational awareness information that could be easily and fast understood through touch.

Language learning is the process by which humans acquire the capacity to perceive and use words to understand and communicate [4]. For every field of knowledge addressing human language and communication, the language learning process

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is very different whether it is the first or second language. While the first refers to an infant's acquisition of the native language, the second deals with the process of learning an additional language when a native one has been already learned.

Learning a second language is a complex process extensively studied in neuroscience [5], applied linguistics [6], sociolinguistics [7], psychology [8], and education [9]. With no intention of further reviewing this process, we shall limit the discussion to state that humans learn a second language by making relations with their own native language, by memorizing, and by practicing. Think of a Spanish-speaking native learning Italian; as both are Latin-based languages, relations can be easily established. However, for a Spanish-speaking native learning Chinese, memorizing new vocabulary and grammar rules as well as constant practice seem the only way.

Language learning does not refer exclusively to spoken languages. Natural languages such as semiotics, sign language, gestural/body language, and tactile patterns are equally used to communicate ideas without conveying any sound. Regardless of their complexity, natural languages also require certain amount of time, effort, and practice in order to master their usage.

In particular, tactile patterns have received growing attention in several domains of human–computer interaction such as virtual reality, sensory augmentation, sensory substitution, robotics, mobile and wearable devices, game and entertainment, among many others. Short structured tactile patterns called tactile icons or tactons [10] have been used to code verbal language and convey information to touch especially in applications where sight and hearing are restricted or overloaded.

Tactons have been already studied to encode simple information such as flight data for pilots [11, 12], warning signals for car drivers [13] and clinicians [14], instructions for improving physical performance [15, 16], navigational assistance for visually impaired and blind people [17, 18], emotions [19, 20], and verbal words [19, 21]. In these studies, different sets of tactons were proposed to test subjects and satisfactory recognition rates were reported. However, only one tacton was recognized at a time.

In this study, we present several tactons to a group of 20 voluntary subjects and we combine them to construct sentences that represent gradually more complex information. We seek to evaluate human performance in tactile language learning and tactile memory and to determine how far we can cognitively handle tactons for more ambitious applications in human–computer interaction, wearable/mobile computing, and assistive devices. For this evaluation, we propose a novel approach: podotactile stimulation. Tactile-foot stimulation has shown interesting results and great potential in our previous studies [17, 19, 22].

The rest of the paper is organized as follows: Sect. 2 presents a brief review of relevant prior related work. Section 3 presents a technical overview of the apparatus used in this study. Section 4 evaluates human performance in tactile learning, tactile memory, and tactile language usage with the proposed device while Sect. 5 shows an example of situational awareness assistance with tactile language. Finally, Sect. 6 concludes with main remarks and future work perspectives.

2 Related Work

Let us start by defining the three main concepts addressed in this paper: tactile learning, tactile language, and tactile memory.

Tactile learning is the process of acquiring new information through tactile exploration. It is a process that does not happen all at once but is built upon practice.

Tactile language is a set of tactile information that can be used to construct a communication system. As oral languages, tactile ones contain a set of rules that govern how tactile information is used to form sequences meaning phrases.

Tactile memory refers to the persistence of learning in a state that can be revealed at a later occasion. It can be either long-term- or short-term memory. While tactile information stored in the long-term memory affects our world perception and influences our interaction with the environment, tactile information in the short-term memory is held in mind in small amount for a short period in an active readily available state [23].

Several studies evaluating these three concepts using more than a simple set of few tactons can be found on the literature.

F. Geldard conducted in 1957 one of the earliest attempts to evaluate tactile memory. He proposed to encode symbols of the alphabet with vibratory patterns. Guided by this reasoning, Geldard design the Vibratese language, which was composed of 45 basic elements; the tactile equivalent of numbers and letters [24]. About 12 h of practice were required to learn the language. Subjects were able to recognize single letters but could not interpret continuous sequences of patterns correctly.

During the 70s, experimental research on understanding tactile sequences provided the first interesting insights into the capabilities of tactile memory: Gilson and Baddeley [25] and Sullivan and Turvey [26] concluded that tactile memory works best for stimuli lasting 5–10 s and that people quickly forget tactile stimuli. Watkins and Watkins [27] and later, Mahrer and Miles [28] evidenced the importance of training for memorizing tactile sequences. Handel and Buffardi [29] experimentally observed that it is not only possible to learn and understand tactile sequences but to encode also statistical regularities to predict patterns within the sequences.

Conway and Christiansen [30] conducted experiments to compare the ability of learning sequences with hearing and touch. Ten different sequences combining from three to five elements each were displayed to both senses. Results showed that the auditory modality displays a significant learning advantage compared to touch.

Evreinova et al. proposed in [31], a memory game destined to strengthen the short-term tactile memory of hearing impaired adults. Ten participants explored 27 different vibrotactile patterns using the Logitech tactile feedback mouse. Results reported that after a significant learning time, subjects could reasonably manipulate the set of tactons. No concatenation of tactons was reported.

Wang et al. presented in [32], a computer implementation of the classic memory card game using the STreSS tactile display. Twelve tactile memory cards had to be matched with their visual counterparts. After a short training period, the cards could be distinguished from one another using tactile stimuli alone. Vision shortened the learning process.

Kuber et al. described in [33], a multimodal memory game for the blind. Combining speech, nonspeech audio, and tactons, both sighted and blind users achieved to replicate complex sequences of information. Concatenation of nonvisual information was reported with good results; however, multimodality eased the task. Similarly, Raisamo et al. proposed a tactile memory game using visual, audio, and tactile feedback [34]. The game got a positive response from a group of seven visually impaired children.

Oliveira and Maciel presented in [35] the design and assessment of tactile vocabularies to support navigation in 3D environments. Two approaches were explored: prefixation and tactile sequences. Using an eight tactor belt, vibrating patterns encoding obstacle, destination, course, warning, and itinerary information were conveyed to the user to enhance the visual navigation of virtual scenarios. Prefixed patterns were easier to learn and memorize than tactile sequences.

Barber et al. conducted in [36] a study involving three categories of tactons: static, dynamic, and directional. While static tactons consisted of constant patterns, dynamic and directional tactons consisted of a set of sequential subpatterns that transmit the sensation of motion. Static and dynamic tactons represent words while the directional ones describe some type of navigational context. Their results showed that through the pairing of dynamic and directional tactons, users were able to interpret two-tacton sentences with an accuracy of 92%.

Finally, Riddle and Chapman proposed in [37] a five step methodology for building tactile languages. The first step is to define the message set. Defining the message set consists of identifying the concepts to be communicated either for many different tasks or situations or for specific uses. The second step seeks to determine the physical characteristics of vibrations such as vibrating frequency, pulse duration, and sequence of activation. The third step is to define application-specific design rules so that tactile parameters have implied meaning. If these meanings can be linked to the inherent meaning of messages, patterns would be intuitive and easy to learn. The fourth step is the creation of the tactons while step 5 evaluates the tactons to validate their design and performance.

Note that most of the applications cited in this section were developed in the context of human–computer interaction, virtual reality, and serious games. However, much of their basic research comes from the fields of psychology, cognition, and neurolinguistics.

3 Tactile Display for the Foot

Much of what is found in the literature about tactile feedback concerns tactile stimulation of the fingers and hands. However, the acuity of other body areas has been explored as well: the wrist/forearm [14], abdomen [38], chest [39], tongue

[40], ears [41], head [42], and even the backside [43] have been studied to transmit information to a user. The devices are as diverse as the technology used and the location on the body.

Since 2008, we have been studying the role of one of the less explored body locations in tactile perception: the human foot. We seek to understand how people perceive information through their feet and to evaluate whether this perception level can be exploited in different human–computer interaction tasks.

For this purpose, we have developed several prototypes of electronic tactile displays for the foot. In particular, the newest design (Fig. 1a) consists of four vibrating actuators that stimulate the medial and lateral plantar areas of the foot sole which concentrate most of the mechanoreceptors sensitive to vibrotactile stimulation [44, 45].

In this prototype, vibrators are arranged in a diamond-like shape with 35 mm side-length (Fig. 1b). All four actuators are integrated in a commercial inexpensive foam shoe-insole. They provide axial forces up to 13 mN and vibrating frequencies between 10 and 55 Hz. Each vibrator is independently controlled with a specific vibrating frequency command [19].

This version is intended to be used on the left foot and is fully wearable (Fig. 1c): it includes an RF (radio-frequency) transmission module which allows simple and reliable point-to-point communication with a computer within a range of 100 m. It also includes the electronic drive to power the vibrating actuators and an on-board power supply that ensures 6 h of autonomy. Figure 1c inset details the electronic module that the user carries comfortably attached to the ankle.

Experimental perceptual studies have been already conducted with our prototypes in sighted and blind users. We have tested navigational direction recognition, shape identification, pattern and emotion recognition, vocabulary learning, and real-time navigation in space [17, 19, 22]. Our results indicate that people actually understand information displayed to the plantar surface of the foot. However, this information must not be complex as the foot is not capable of precise discrimination. Information displayed to the feet must be simple and preferably, encoded as short structured vibrating patterns (tactons).

One of the most challenging applications for this device is perhaps the assistance of visually impaired people: this mechatronic shoe-insole could be used for providing diverse information such as directions for independent navigation and situational awareness assistance.

An attractive feature of this device is that it can be further inserted into a shoe making it an inconspicuous and visually unnoticeable assistive device. Unlike other portable/wearable assistive devices, an on-shoe device does not heighten the handicapped image that affects the user's self-esteem.

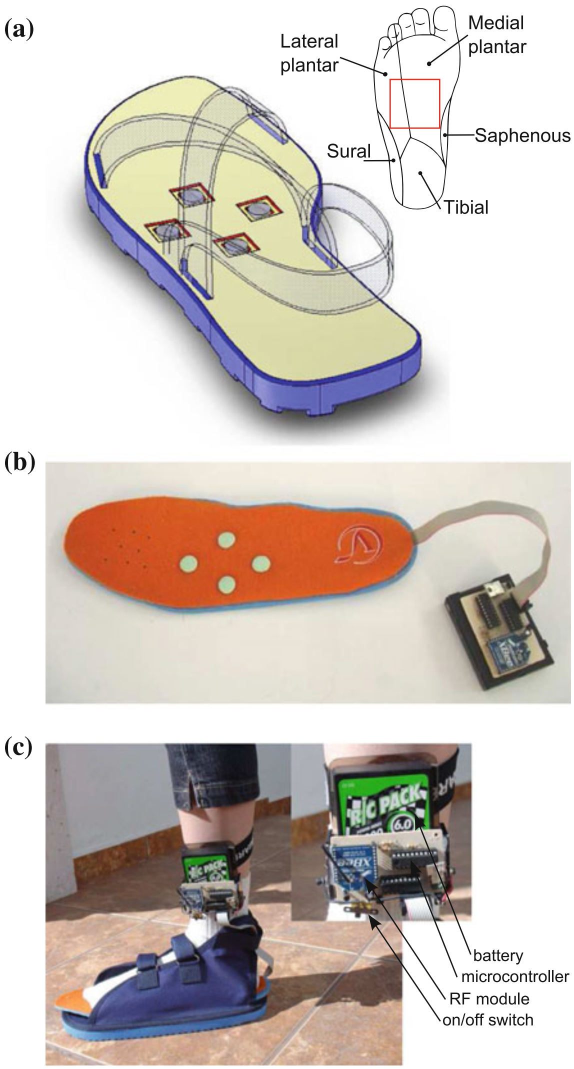

Fig. 1 Tactile display for the foot: **a** Design concept. *Inset*: target stimulation area enclosed in *square*. **b** Prototype. **c** Fully wearable device with wireless connection. *Inset* electronic module

4 Evaluation and Results

Perceptual experiments were carried out to evaluate human performance in tactile language learning and tactile memory using this prototype.

We reported in the past an experiment involving vocabulary learning [19]. For that test, we proposed five vibrotactile patterns or tactons to represent arbitrary five different words. Tactons were presented to test subjects, which were requested to memorize them in a short period of time. Subjects were then asked to identify the tactons. Results were very encouraging: recognition rates indicated that subjects could reasonably manipulate the set of tactons. We wondered then whether tactons could be combined to represent more complex information and subject performance in this case.

4.1 Study Participants and Experimental Procedure

Twenty undergraduate students (16 men and 4 women) at Panamericana University participated voluntarily in the experiments. All gave their consent in agreement with the university ethics guidelines. No special criteria were used to select them but availability. None of the participants reported problems in tactile sensory or cognitive functions. Their ages ranged from 18 to 24 years old with an average age of 20.8. None of them had tried any of our tactile display prototypes for the foot before.

To avoid any possible distraction, experiments were conducted in a restricted access laboratory where it just remained the test subject and the researcher. During the experiments, the subjects were seated wearing the tactile display on the left foot and a headphone set. Audio cues generated by the vibrating motors were discarded with a pink noise provided by the headphones. For hygiene, all subjects were requested to use socks. Before each session, they were totally naive about all aspects of the test and were given general instructions concerning the task. A short familiarization time with the device was granted prior to the tests. Each subject was asked to perform four experiments and to fill out four answer forms. All of this took on average 25–30 min.

For statistical analysis, subjects were randomly divided into two groups of 10. The χ^2 distribution was used to evaluate difference in proportions across samples of a same group while the z-test to give a confidence interval for the true difference in proportions between groups. The level of significance to reject the null hypothesis (α) was set to 0.05 in all cases.

4.2 Experiment I: Vocabulary Learning

The purpose of the first test is to present the set of tactons to the subjects and to evaluate whether they could quickly learn and retain them in memory.

4.2.1 Method

Four tactons were chosen for this test: boy, play, ball, and big. The vibrotactile patterns in Fig. 2 were arbitrarily chosen to represent these words. For example, ‘boy’ in tactile language is represented by a long vibration followed by two short ones while ‘play’ by a long vibration followed by a short one, and again a long vibration.

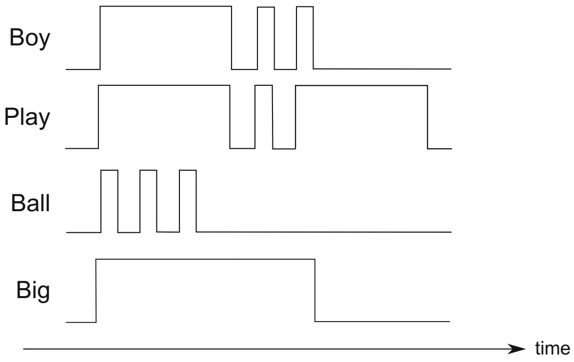

Fig. 2 Tactons representing arbitrarily four words. Set times for short and long vibrations are 0.5 and 3 s, respectively. Set time for 'big' (the longest vibration) is 5 s. For all tactons, all four vibrating motors in the display are actuated simultaneously at a vibrating frequency of 55 Hz

Subjects were asked to match what they felt tactually with one of these words. Before the test, all four tactons were displayed to the subjects so that they could make a mental representation of them. Upon request, they could have the tacton refreshed on the display. When ready, the tester made a 1 min small talk on purpose to distract their minds from the test. The test consisted of a single trial. Each tacton was randomly displayed twice. Subjects had no time restriction to provide their answers and they were allowed to modify them if they felt they had made a mistake.

4.2.2 Results

Figure 3 shows the results obtained. For group 1 the average recognition rates were 80, 90, 90, and 90% for boy, play, ball, and big, respectively. For group 2, these were 70, 75, 85, and 90%, respectively. Recognition rates suggest that the proposed tactons were easy to learn and to remember.

Subjects in both groups exhibited a uniform performance across the test (group 1: $\chi^2 = 1.37$, $p = 0.71$, group 2: $\chi^2 = 3.12$, $p = 0.37$). There was no statistically significant difference in the performances of the two groups ($p > 0.05$).

4.3 Experiment II: Constructing Sentences with Two Tactons

The purpose of this test is to evaluate subject performance when combining two tactons. This test would require a higher level of concentration and is a first step toward constructing sentences that describe more complex situations.

4.3.1 Method

Tactons were combined in pairs to form four sentences: big-boy, boy-play, big-ball, and playball. Sentences were displayed as in verbal communication: one tacton first, then a short pause, then the second tacton.

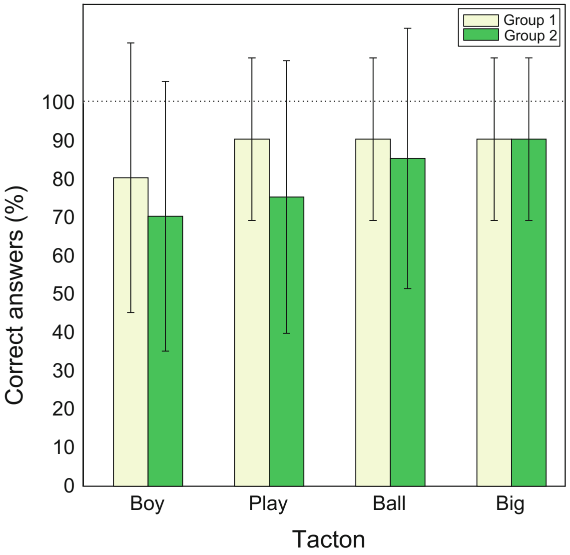

Fig. 3 Performance of the 20 subjects at learning and memorizing the set of tactons ($p > 0.05$). The standard error is shown as an *error bar*

Subjects were asked to feel the entire sentence before reporting the words perceived. They were not aware about the sentences so they could report any possible combination. The test consisted of a single trial. Each sentence was randomly displayed twice. Subjects had no time restriction to provide their answers and they could have the tactile sentence refreshed on the display upon request.

4.3.2 Results

Figure 4a shows the results obtained. For group 1, the average recognition rates were 65, 80, 80, and 75% for big-boy, boy-play, big-ball, and playball, respectively. For group 2, these were 85, 75, 90, and 65%, respectively. Even though this task was more complicated, recognition rates did not decrease substantially.

As in the previous test, subjects in both groups exhibited a uniform performance across the test (group 1: $\chi^2 = 1.6$, $p = 0.65$, group 2: $\chi^2 = 4.4$, $p = 0.22$). Again, there was no statistically significant difference in the performances of the two groups ($p > 0.05$).

Scores presented in Fig. 4a refer to totally correct sentences, that is when subjects recognized both tactons. However, it is interesting to appreciate in detail subject performance. Figure 4b shows the average distribution of both correct and wrong answers. For example, for sentence big-boy, the 65% of the answers provided by subjects in group 1 indicate that they recognized successfully both tactons while the remaining 35% indicate that they recognized one tacton but failed to do so

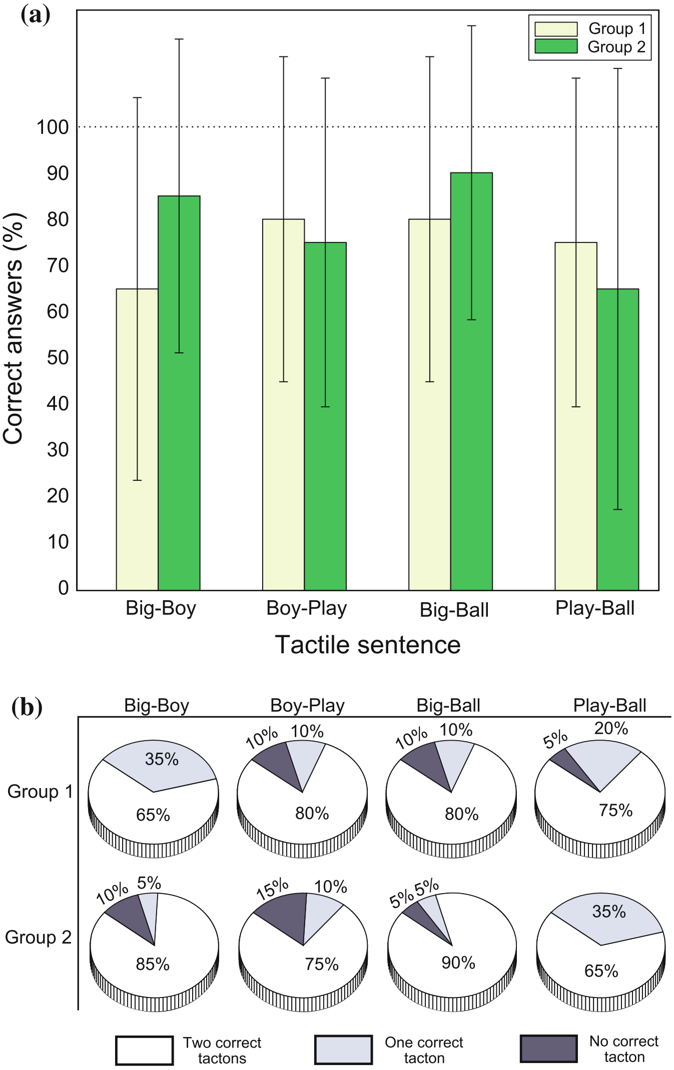

Fig. 4 **a** Performance of the 20 subjects at recognizing tactile sentences with two tactons ($p > 0.05$). **b** Average distribution of both correct and wrong answers

for the other. Similarly, the 85% of the answers provided by subjects in group 2 indicate that they recognized both tactons, 5% only one, and 10% that they did not recognized any tacton. Note that for most incorrect sentences, subjects tend to recognize at least one tacton.

4.4 Experiment III: Constructing Sentences with Three Tactons

The third test proceeds to evaluate subject performance with sentences containing three tactons.

4.4.1 Method

Tactons were combined in triples to form three sentences: big-boy-play, boy-playball, and play-big-ball. Again, tactile sentences were displayed as in verbal communication: one tacton first, a short pause, then the second tacton, a short pause, and finally the third tacton.

As in the previous tests, subjects were asked to feel the entire sentence before reporting the three words perceived. They were not aware about the sentences so they could report any possible combination. The test consisted of a single trial. Each sentence was randomly displayed twice. Subjects had no time restriction to provide their answers and they could have the tactile sentence refreshed on the display upon request.

4.4.2 Results

Figure 5a shows the results obtained. For group 1, the average recognition rates were 70, 85, and 75% for big-boy-play, boy-playball, and play-big-ball, respectively. For group 2, these were 70, 80, and 80%, respectively. Note that subjects practically obtained the same recognition rates as with sentences with two tactons. It was observed that subjects requested more often to refresh the sentence on the display, but only at first; subjects quickly arrived to get concentrated and manage the three tactons.

Subjects in both groups exhibited again a uniform performance across the test (group 1: $\chi^2 = 0.74$, $p = 0.68$, group 2: $\chi^2 = 1.3$, $p = 0.52$) and there was no statistically significant difference in the performances of the two groups ($p > 0.05$).

Figure 5b presents the average distribution of answers. Note that for most incorrect answers, subjects did recognize one or two tactons. Answers with all three tactons incorrect are the less.

4.5 Experiment IV: Constructing Sentences with Four Tactons

The final test combines all four tactons to form the longest sentences that will be presented to the subjects.

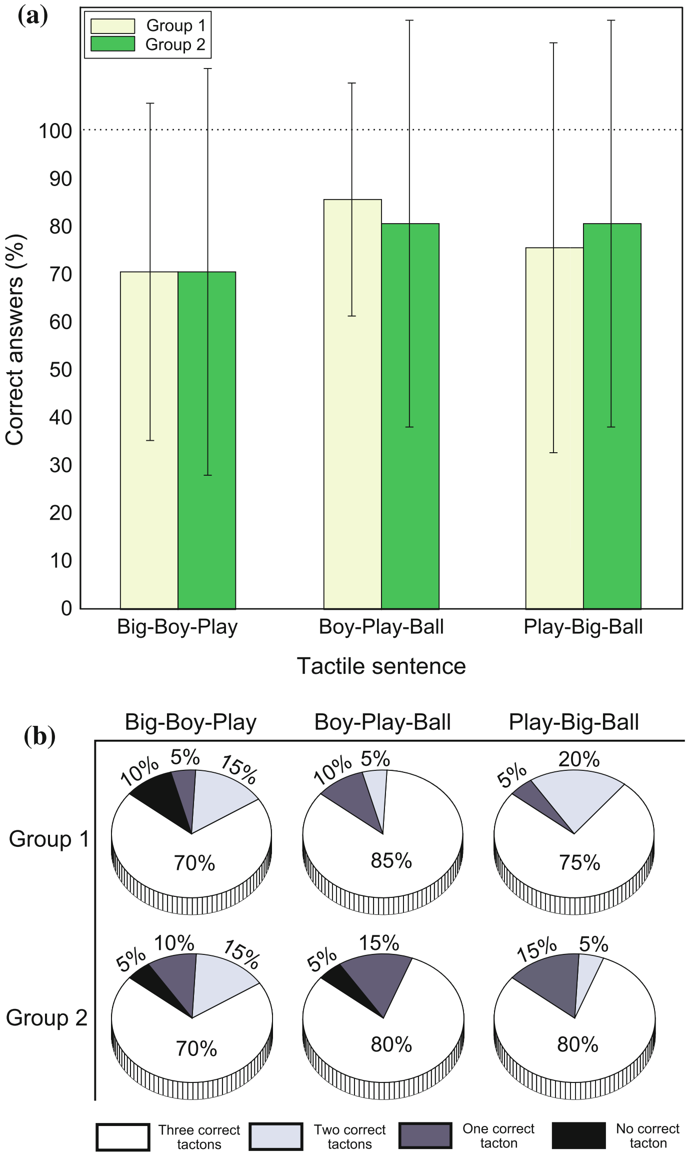

Fig. 5 **a** Performance of the 20 subjects at recognizing tactile sentences with three tactons ($p > 0.05$). **b** Average distribution of answers

4.5.1 Method

Tactons were combined in quads to form two sentences: big-boy-playball and boy-play-big-ball. Again, tactile sentences were displayed as in verbal communication: an alternating sequence between tacton and pause.

The same protocol was followed: subjects were asked to feel the entire sentence before reporting the sequence of words perceived. They were not aware about the sentences so they could report any possible combination. The test consisted of a single trial. Each sentence was randomly displayed twice. Subjects had no time restriction to provide their answers and they could have the tactile sentence refreshed on the display upon request.

4.5.2 Results

Figure 6a shows the results obtained. For group 1, the average recognition rates were 65 and 55% for big-boy-playball and boy-play-big-ball, respectively. For group 2, these were 70 and 75%, respectively. Note that subjects in group 1 dropped their performance while subjects in group 2 maintained it reasonably. The results for group 1, however, are heavily skewed by the low performance of three subjects.

For this last test, subjects in both groups exhibited again a uniform performance across the test (group 1: $\chi^2 = 0.42, p = 0.5$, group 2: $\chi^2 = 0.12, p = 0.72$) and there was no statistically significant difference in the performances of the two groups ($p > 0.05$).

Figure 6b shows the average distribution of answers. Note that for most incorrect answers, subjects did recognize half of the sentence. Answers reporting no correct word were rarely observed.

4.6 Discussion

All four tests show that tactons can be quickly learned and retained in memory. Furthermore, these experiments show that tactons can be combined into sentences that represent more complex ideas and that tactile sentences containing up to four tactons can be cognitively handled with high accuracy.

At each experiment, subjects in both groups observed a uniform performance across the test and no statistically significant difference in the performances between groups was found. However, performance of subjects in group 1 was statistically significant different across the four experiments ($\chi^2 = 11.66, p = 0.008$).

Figure 7 shows the evolution of the mean of correct answers across the four experiments for both groups. Note that performance of group 1 progressively decreases while that of group 2 remains reasonably constant. Also note that for both groups, performance is practically the same for sentences with two and three tactons.

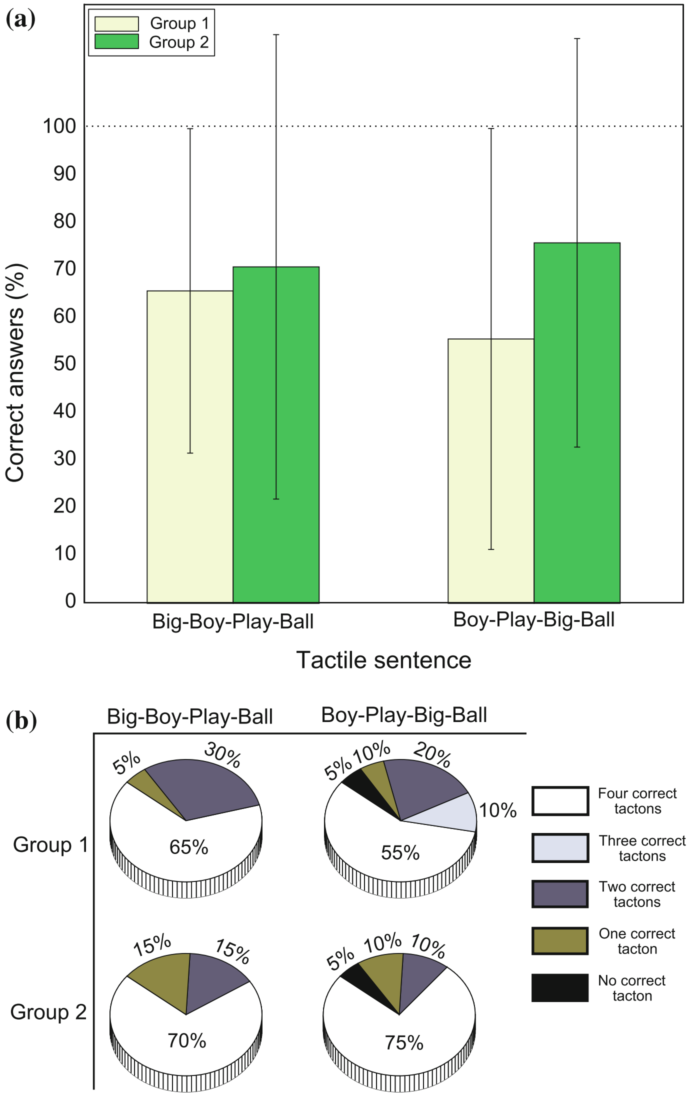

Fig. 6 **a** Performance of the 20 subjects at recognizing tactile sentences with four tactons ($p > 0.05$). **b** Average distribution of answers

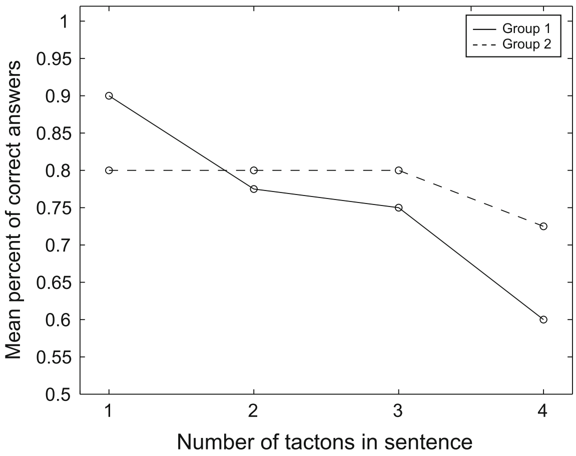

Fig. 7 Evolution of performance across the four tests. Subjects in group 1 exhibit a statistically significant different performance ($\chi^2 = 11.66$, $p = 0.008$) while subjects in group 2 do not ($\chi^2 = 0.95$, $p = 0.8$)

5 An Example of Situational Awareness Assistance During Navigation with Tactile Language

Independent and secure navigation in a real environment is one of the most challenging daily tasks people with visual impairments face having a direct impact on quality of life, on well-being, and on social integration.

As aforementioned, the main aim of the on-shoe tactile display is to assist the navigation of visually impaired and blind individuals. The purpose of this test is to evaluate if it possible to manage directional information and tactile language representing situational awareness at the same time.

5.1 Directional Information

We previously reported in [19], a tactile rendering approach for directional information that has achieved high recognition rates.

This approach consists on setting a navigational direction to each one of the four contact pins: forward **F**, backward **B**, right **R**, and left **L**. A navigational direction is encoded in five sequences (t1–t5) as follows: three consecutive short vibrations in the corresponding contact pin, then a short vibration in the opposite contact pin, and again a short vibration in the correct contact pin.

Figure 8 shows for example, the codification for going forward. Note that the contact pin **F** vibrates three times, then **B** once, and again **F**. Average recognition rates obtained from a group of 20 voluntary subjects were 91.65, 91.25, 78.75, and 91.65% for **F**, **B**, **L**, and **R**, respectively [19]. These figures suggest that people easily and intuitively associate the tactile patterns to navigational directions.

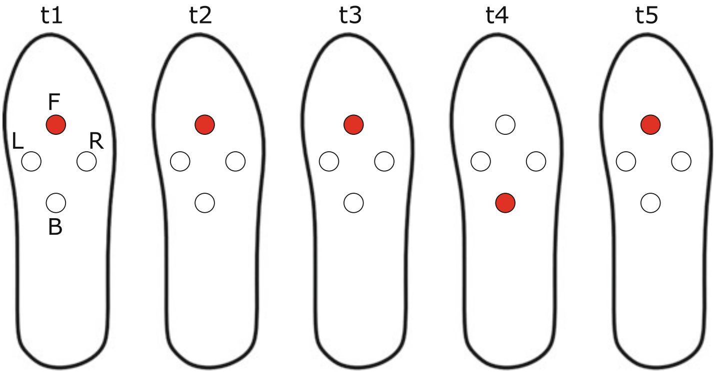

Fig. 8 Schedule of activation of the vibrating motors for the navigational direction rendering (example for going forward)

5.2 Navigation

5.2.1 Method

A camera-based tracking platform was set for this experiment. It consisted of a camera placed 4 m above the ground surface that recorded RGB video. The acquired video was later processed in a PC for subject tracking.

To have an idea of a typical performance that is not skewed by good or poor performances, one of the 20 voluntary subjects was chosen for the experiment: a female exhibiting the median average performance in understanding tactile sentences.

The tactons shown in Fig. 8 were used for pointing her to a navigational direction. A fifth pattern consisting of two consecutive short vibrations, then a pause, and then two consecutive short vibrations (the typical pattern for SMS alerts in mobile phones) was used for indicating to stop. Patterns describing ‘ball’ and ‘big’ (Fig. 2) were redefined to ‘chair’ and ‘obstacle’, respectively. Subject was trained in learning the seven tactons as described in Sect. 4.2.

Tactons were provided by a computer located outside the navigation environment. During the test, the subject was blindfolded so that no cue from sight could be obtained. A navigational environment (Fig. 9) was proposed to the subject who was totally naive about their structure prior to and during the test.

Subject was requested to move according to the pattern felt and to sit down on a chair located inside the environment when indicated. She had no time restriction to complete the test and, upon request, she could have the tactons refreshed on the interface.

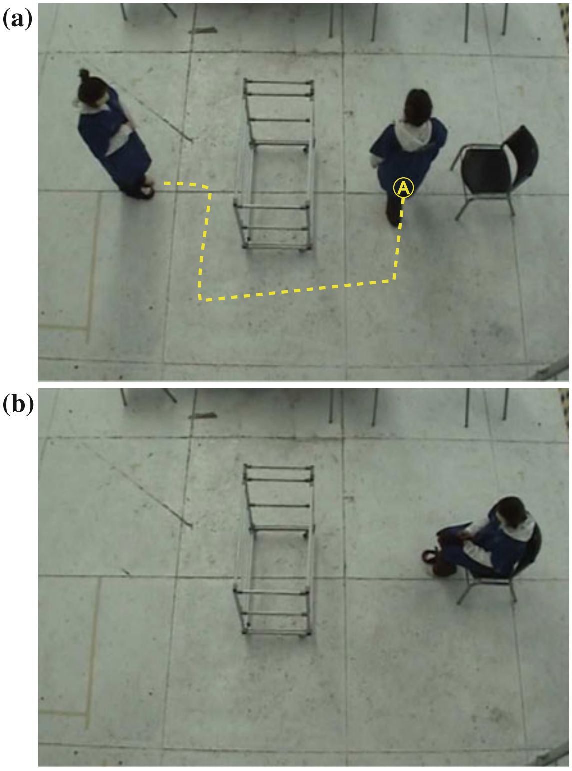

Fig. 9 Situational awareness assistance during navigation: **a** Navigation in a structured environment. The *broken yellow line* represents the trajectory followed by the test subject. **b** Action upon assistance provided by a tactile sentence

5.2.2 Results

Figure 9a shows the results obtained in this test. Subject successfully followed 11 navigational instructions to reach point **A** *(forward-stop-turn right-forward-stop-turn left-forward-stop-turn left-forward-stop)*. At point **A**, a four-tacton sentence displays: *obstacle left, chair right* (Fig. 9a). Subject acts accordingly (Fig. 9b).

Note that the obstacle/chair prefix changed the meaning from actually going to just pointing directions. Semantics relations like this one can be easily established by subjects.

6 Conclusion

This paper presented the results of user studies showing the ability to learn, memorize, and use tactile words.

Vibrotactile patterns or tactons abstractly representing verbal language can be understood, quickly learned, and retained in memory. Furthermore, sentences involving two, three, or four tactons can be constructed and recognized with high accuracy, which broadens the possibilities for describing complex situations that could improve interaction with mobile and wearable computers and in particular, situational awareness feedback provided by assistive devices.

An interesting observation from these tests is that tactons are retained in short-time memory. A follow-up study revealed that after one week without any practice; most of the test subjects could only recall the pattern associated to 'big'. After a month and without any further practice, no tacton could be identified by any of the 20 subjects. Nevertheless, with constant practice (case of visually impaired and blind individuals), tactons could work in long-time memory.

Results obtained from the tests seem very promising for podotactile stimulation. Tactons applied to the foot can be understood and their predefined meaning can be easily associated. Future work will evaluate the perceptual load of tactons and tactile sentences. This work will seek to determine for how long and under which circumstances a user manages to be fully concentrated in tactons before getting tired or distracted. Several high perceptual load conditions will be tested such as noisy environments and crowded spaces at several tacton presentation rates: rare, constant, and high.

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Vision Restoration with Implants

Akos Kusnyerik, Miklos Resch, Huba J. Kiss and Janos Nemeth

1 Introduction

Up until now there has been no available treatment for diseases causing the permanent impairment of retinal photoreceptors. Currently, the development of the retinal prostheses is the earliest to promise a result that can be implemented in the clinical treatment of these patients. To date two different types of retinal prostheses are commercially available, the Retina Implant approved the CE marking in 2013, and Argus II implant achieved FDA approval in the same year. Besides the diseases of the retinal photoreceptors, the permanent impairment of other retinal cells or diseases and injuries of the optic nerve or optic pathway are also causing severe and untreatable conditions.

Implants with different operating principles and in various stages of progress are presented in details, highlighting the characteristics of the development.

Despite of the considerable development of ophthalmologic microsurgery techniques and medical treatment modalities many eye diseases remained untreatable. According to the WHO survey the number of blind people is approximately 39 million [1–3]. The “Vision 2020” program that was started in 2000 by the World Health Organization aims to extinguish the causes of avoidable blindness and to reach a significant decrease in the number of the visually impaired people [4, 5, 6]. The WHO “Universal Eye Health, a Global Action Plan 2014–2019” has initiated a new program in 2014 to reduce the visual impairments worldwide by 25% till the end of 2019. To fulfill the goals of the programs is difficult, since the increase in both the number and the average age of the human population makes a higher and higher incidence of blindness [3].

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In developed countries degenerative diseases of the retina play a leading role in the causes of the blindness [7]. Destruction of the photoreceptors is common in both retinitis pigmentosa and age-related macular degeneration. Currently at the end-stage of degenerative retinal diseases, improvement of the vision may be achieved only by the different retinal implants.

Vision restoration implants are devices that induce visual experience by the stimulation of the remaining and functional cells of the retina, optic nerve, visual pathway, or visual cortex. Retinal implants are devices that induce visual experience by the stimulation of the remaining and functional cells of the retina. The implantable retinal implant is called vision restoration implant, and it includes a retinal chip, as well. Elementary visual light experiences, the so-called phosphenes have been achieved in the 50s by the help of electrodes implanted directly into the brain [8]. Because of the numerous technical difficulties these experiments were suspended, and research in this field was restarted only recently [9–11].

The continuous evolvement of microelectronics and engineering achieved the development of devices becoming highly similar to the light-sensitive retinal structures. Such an intra-retinally implantable device replaces the photoreceptors, and generates biological signals induced by the incoming light. Our aim in this chapter was to introduce the reader to these techniques and field, and to compare the simultaneous developments of technical novelties and clinical studies.

2 Early Historic Developments

The “silicone retinal chipsets” was the first attempt in the imitation of the function of the human retina by integrated circuits. However, the lack of the knowledge of retinal modeling, these devices remained as engineering specialties, being able to mimic only external retinal effects [12].

Intense intraocular implant research began at the early 90s. The most obvious solution seemed to be the use of subretinal implants, since subretinal implants “only” need to replace the generation of the electronic signals as a response to the visible light. The main difficulties of this technique are the proper design of the metal electrode, its biocompatibility and the elimination of the charge accumulation.

The next possibility is the epiretinal chip. Here a serious preprocessing is required to replace the function of the retina by mimicry. The “Bionic Eye” architecture serves as the core of this design [13]. The pioneer of the epiretinal chipsets is Marc Humayun, the ophthalmologist researcher of the University of Southern California. His fellow researcher, professor Wen-Tai Liu of the University of California at Santa Cruz created the first chipsets with a resolution of 4 by 4 than 8 by 8. These were implanted into humans with moderate success [14].

The more detailed information discovered on the structure of the mammalian retina lately [15] made a new situation in the field. Since the output of the retina is not only a single image but a summary of different frames, and since the attachment surface may not be too small, channels could be short-circuited easily. Due to these technical difficulties the exact modeling of the retinal channels by the cellular retina chip is rather impossible [16]. This discovery made certain research groups shift to the development of subretinal implants [17].

In the following, we are going to summarize the main properties of the different retinal implants and to detail the indications of their implantation.

3 Types of the Implants

1. Intraocular implants

Since the energy of the visible light reaching the retina currently is not enough to operate the implant, independently of their location, all implants have an external energy source. Implants can be grouped by their localization to the retina. Implants attached to the vitreal surface of the retina are the epiretinal, while implants attached to the pigment epithelium under the retina are the subretinal implants. Figure 1 summarizes the possible locations of the chipset related to the retina. The energy for the amplification of the light reaching the chipset, the data processing, and analysis of the data is coming from the external unit. Depending on the operational mechanisms the epiretinal chipsets (Fig. 1a) could be connected not only to external energy sources, but as well as cameras integrated into the frames of glasses. At subretinal chipsets (Fig. 1b) the implant is directly stimulated by the visible light and thus requires only an energy input.

1.a. Epiretinal implant

The epiretinal implant is located on the vitreal surface of the retina. It has multiple segments located at the place of the crystalline lens, or integrated in the frame of the glasses, as well as in the external unit. The intraocular chipset has a direct connection to the retina and it is attached to the surface by a specially designed rivet. This design allows the chipset to stimulate all axons of the remaining ganglion cells by the information recorded by the camera in the frame of the glasses directed by head movements.

1.b. Subretinal implant

The characteristic property of the subretinal prostheses is that they are localized between the retinal pigment epithelium and the layer of the destroyed photoreceptors. Their other specifics may differ. The intraocular unit of the most advanced subretinal implant contains 1.500 microelectrodes. The wire starting from the chipset runs between the pigment epithelium and the neuroretina, perforates the sclera and goes into the orbital cavity. The design is highly similar to the cochlear implants designed for people of hearing loss [17, 18].

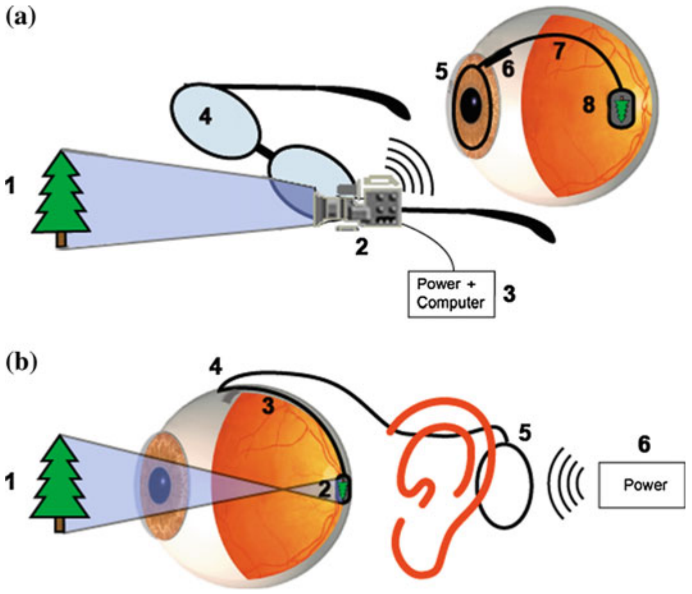

Fig. 1 Figure Illustration of the intraocular implants. **a** The design of the epiretinal implant. **b** The design of the subretinal implant. **a** The design of the epiretinal implant. *1* The object in the visual field of the camera integrated into the glasses; *2* the camera integrated into the glasses, recording motion pictures; *3* the unit processing the recorded movie with the power unit; *4* glasses with camera and transceiver; *5* intraocular coil designed for wireless signal forwarding; *6* postprocessing unit between the recording unit and the implant; *7* intraocular wire; *8* epiretinal implant, **b** the design of the subretinal implant. *1* The object in the visual field of the chip; *2* the subretinal implant; *3* wire under the retina; *4* fixation plate attached to the sclera; *5* power unit implanted subcutaneously behind the ear; *6* outer power and processing unit

2. **Extraocular implants**

Extraocular prostheses outside of the eyeball exist, as well. They are located either intraorbitally or intracranially. On this field researchers are faced by numerous difficulties as biocompatibility, convenient electrode design or the stimulation patterns of the electrodes.

2.a. **Optic nerve device**

There are current experiments using an extraocular but intraorbital implant having a device fixed ring-wise on the optic nerve (Fig. 2) [19].

2.b. **Thalamus device**

An appropriate place of microstimulation would also be the lateral geniculate body of the thalamus, as it is an important part of the visual pathway. Pezaris et al. confirmed this approach lately in successful monkey experiments [20, 21].

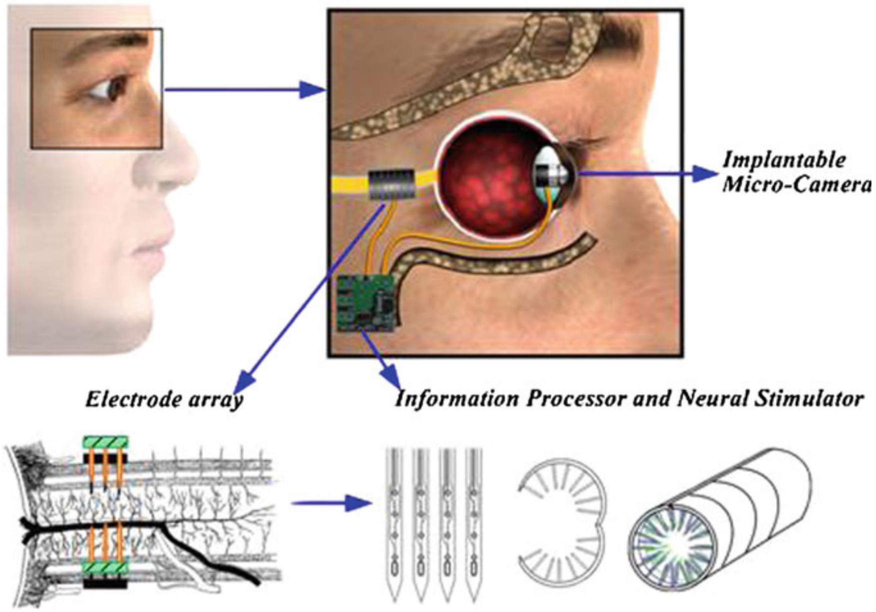

Fig. 2 Figure illustration of the ring-shaped optic nerve implant (C-sight project)

2.c. Cortical visual implant

An additional approach is that of cortical devices and electrodes which are placed directly to the visual cortex. First Brindley than Dobelle et al. had experiments of phosphen responses evoked by such electrodes [22–24].

The cortical device is using an external camera with an integrated image analyzer to transfer the processed signal to the central computer unit [24]. This unit is stimulating the remaining cells and structures according to the requested patterns [25]. Limitation of this approach is the complete development of an image-processing system to convert an electronic image captured by a camera into a real-time data stream [24].

However, human trials of the next generation of cortical visual implants are imminent [24, 26]. Recently, Second Sight announced the first successful implantation of Orion I Visual Cortex Prosthesis.

4 Indications

1. Indications of intraocular implants

The retinal implants are most useful in bilateral cases when both eyes are damaged and the patient is blind. The retinal implants are able to work only in case of those retinal diseases which did not involve the whole retina and the ganglion cells and so

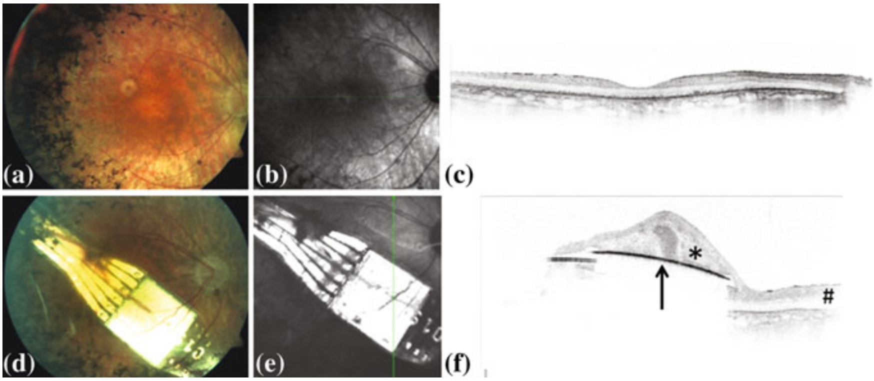

Fig. 3 Localisation of the subretinal implant in the right eye of one of the patients with end stage retinitis pigmentosa, undergone surgery in Semmelweis University, Budapest, Hungary. **a** Fundus photograph showing optic nerve, narrow retinal arterioles and venules, atrophic macula and pigment clumps in the peripheral retina. **b** Infrared fundus image of the same ye, green line represents the site of the scan shown on Fig C. **c** Optical coherence tomographic (OCT) image characteristic for retinitis pigmentosa, demonstrating atrophic choroid and retinal pigmentepithelium. Neuroretinal thickness is low, foveolar morphology is almost normal. **d** Funduscopic image of the same eye 3 months after implantation. Note the subretinal electrode of the implant under the macular region. **e** Infrared image. Note the retinal vessels in front of the implant. **f** OCT cross sectional image of the implant (arrow), and the edematous neuroretina above (*), for comparison intact retinal structure corresponding to retinitis pigmentosa on the left side of the image (#)

the optic nerve and visual pathway are well functioning and they are able to transfer the information and electric signals coming from the retinal implant to the visual cortex. These implants replace the functions of the damaged retinal cells, like the photoreceptors light sensitivity (in case of the subretinal implants) or the photoreceptors and bipolar cells functions (like the epiretinal implants). There are some other important inclusion criteria, like earlier period of appropriate visual functions at least 12 years, adequately perfused retinal vessels, age, no retinal detachment or edema, good inner retinal function, etc. [27]

Degenerative diseases of the retina develop a varied appearance. Among the heritable types of degenerative retinal diseases *retinitis pigmentosa* occurs the most often and with the most homogenous clinical appearance. Progression of this disease depends on many factors; among many others the diverse genetic background influences strongly the outcome. Retinitis pigmentosa is a common name for those diseases, in which photoreceptors of the retina decay progressively making the light unable to evoke responses on the retina. The word retinitis in the name of the disease preserved the formerly believed inflammatory etiology. Previously, the name tapetoretinal degeneration was also used [28, 29], but now the degeneratio pigmentosa retinae and the retinitis pigmentosa are names used. Typically, the visual impairment begins at adolescent age, first the vision loss occurs at twilight and/or at the peripheral vision. Later, the disease may lead to a complete loss of light sensitivity by the young adult age [30]. In this phase, all other elements of the retina except the photoreceptors are at least partially functional [30, 31]. This explains why retinal implants may be useful in these types of diseases: the neural cells of the retina others than the photoreceptors and the visual pathway must be functional to be able to forward the information. That part of the implant, which is attached to the retina, replaces the photoreceptors and directly stimulates the remaining cells with electric stimuli. This is why the target population at the beginning of the testing of these devices was the group of patients affected by this disease. This situation has unchanged. The current major indication of retinal chip implantation is the population of retinitis pigmentosa patients, who are at the end-stage of the disease and whose vision is damaged in such severe way that they are not able to travel alone or to sense the light [32].

If an appropriate improvement of vision becomes achievable among retinitis pigmentosa patients, the use of the implant emerges in other degenerative retinal diseases, such as in *age-related macular degeneration*, one of the leading causes of blindness in developed countries. Other indications might be *cone rod dystrophies* and *choroideremia*.

2. **Indications of extraocular implants**

In case of implants with electric stimulation of the thalamus or visual cortex, the indication is far wider. Theoretically, they are able to restore useful vision for all persons with *acquired blindness* due to any eye disease, including the total destruction of the retina (like in diabetic retinopathy, old retinal detachment), or the eyeball (like in severe cancers and injuries) or in case of the total destruction of the optic nerve (like in glaucoma). In these cases, the electronic devise replaces all the functions of the retina (image capture and primary analysis) and that of the optic nerve (information transfer to the brain).

5 Preclinical Studies

Several preclinical trials of the field were initiated in the last decade and they indicated a strong cooperation between different institutes and workgroups.

One of the latest examples of such cooperation is an *Australian project*. The participants of this consortium are the Sydney University, the University of Melbourne, the Centre for Eye Research Australia, the University of New South Wales, the NICTA, the Bionic Ear Institute, the Australian National University, and the University of Western Sydney. The project is called the Bionic Vision Australia and is led by Professor Anthony Burkitt. Participants of this project had a significant role in the development of the cochlear implant formerly. They aimed to create the prototype of the first human implant and to implant it into patients suffering of vision loss in 2012. Starting of this prototype they plan to develop the second generation of the implants, which would allow face-recognition, reading and a visual acuity of 20/80. Stimulation of this device would be done by 1.000 electrodes and a two-way high-speed communication would be possible between the units. A camera attached to the glasses would record the images, and the processed information would have forwarded to the suprachoroidally implanted chipset wirelessly [33, 34]. Later, they started to develop three different bionic eye devices with different number of electrodes (44 electrodes, 98 and 256 electrodes, respectively).

The "*C-Sight Project*" of China is led by Professor Qiushi Ren. In this project, needle-like electrodes would be attached in a ring-like fashion to the optic nerve penetrating between the nerve fibers (Fig. 2). The Universities of Beijing, Shanghai, and other Chinese Universities participate in this consortium. The animal experiments already started but the following schedule is unknown yet [19, 35, 36].

In the United States several trials were running simultaneously, many of these was expected to reach the clinical phase.

The *Boston Retinal Implant Project* (BRIP) is a joint work between the Harvard University (Professor Joseph Rizzo), the MIT Electronic Laboratories (Professor J. Wyatt), and the Cornell laboratory (CNF). First, they interest concerned epiretinal implants, but recently they expanded their efforts to subretinal implants, as well. Their research profile includes the special electric circuit defendant system, the improvement of the surgical implantation technique and the complete covering of the device to protect the chipset, the wires, and the electrode surfaces [37]. The device has been tested both in vitro and in two Yucatan minipigs [38].

The trial of the Stanford University workgroup, led by Professor Daniel Palanker is both surprising and promising. They develop a flexible, easily implantable prosthesis, which uses the energy of the light, the "*High Resolution Photovoltaic Retinal Prosthetic System.*" According to the original description the processed images from video camera are displayed on a special video goggles, and projected through the eye optics directly onto the retina using a pulsed near-infrared (880 nm) light. These experiments successfully tested in ex vivo and in vivo; the first human trial recruited participants in collaboration with Pixium Vision under supervision of Prof. Jose Sahel [39–42]. The unit called PRIMA planned to be implanted in Paris, at the Quinze-Vingts National Eye Hospital.

The working group of Korea led by Professor Kim started its work named as the "*Korean Artificial Retina Project*" in 2000 at The University of Seoul. Their chipset, attached on a flexible polyimide plate is implanted suprachoroidial. The prosthesis is tested only in animal experiments yet [43, 44]. Their high-density electrode arrays were under investigation focusing on stimulation parameters that were optimized by ex vivo experiments.

In Japan, simultaneously several centers (Gamagori, Tokyo, and Sendai) focusing on the development of retinal implants. The *Japan Retina Implant Group* started by the late Professor Yasou Tano and supported by the Nidek Vision Institute develops *suprachoroidial prostheses* since 2000. They planned to improve the resolution of the implant by the increase of the electrodes [45–49].

There are several articles and reviews presenting and comparing the latest results [24, 25, 47].

6 Clinical Trials and Results

6.1 Argus II Retinal Prosthesis, United States of America

The Argus type second-generation epiretinal chipset is currently available to implant in humans by a group led by Mark Humayun. The clinical trial is coordinated by the firm, Second Sight of California. The resolution of this second-generation prosthesis is 60 pixels, compared to the previous generation 16-electrode Argus I implant. A central processing unit transforms the images recorded by the camera glasses to the 60 electrodes located on the retina. The prosthesis used in this trial was developed by the Lawrence Livermore National Laboratory.

The device is composed of three units: the camera integrated into the glasses, connected to a signal forwarding system. The signal is sent to the central computer unit, that transcodes the signal into electric impulses. The third unit of the prosthesis is the implantable unit containing a thin net of tiny electrodes and a signal receiver. The prosthesis has been implanted into 36+ participants (Argus I: 2002–2004: 6; Argus II: 2005-: 30+). Patients could often—but not always—sense and identify the light and moving objects. One of the patients could identify and follow an inch-wide line painted on the floor. According to the data published in peer-reviewed, different kind of visual function assessments were performed: (1) square/object localization, (2) direction of motion and (3) discrimination of oriented gratings (a.k.a. visual acuity). In the trial real-world orientation and mobility (O&M) tests were also explored: a test where patients located a door and a test, where patients were asked to follow a line on the floor.

Adverse events experienced by Argus II recipients occurred in the early postoperative period. The detailed data on the adverse events are awaiting publication [26]. In two cases a severe ophthalmic inflammation, endophthalmitis occurred [50, 51].

6.2 The Epi-Ret3 Trial, Germany

In the IMI-IRIS study of a German consortium led by Professor Gisbert Richard an epiretinal implant is used in an approach similar to that of the American researchers. In the first phase of these studies, the chipset was implanted for the duration of less than an hour. Recently, the third phase is in progress that was started in 2007. In their latest papers they published details of the implantation method, the following removal and the achieved results [52, 53, 54]. The prosthesis was implanted into six patients in Essen and Aachen. Thanks to the compact design, the implantable unit has two subunits. The extraocular unit includes the computer and the signal forwarding system. The intraocular unit includes a receiver, a signal processor, and the 25 hexagonally distributed, iridium oxide covered electrodes having a diameter of 100 μm each. By induction, the device is controlled remotely, wirelessly.

The tests were performed in 4 weeks following the surgery. All the patients could identify the stimulations of the electrodes as flashes of light. During the stimulations they discovered, that the evoked responses have a stronger correlation with the width of the stimulus as its intensity [54].

In this project implantations are not performed recently, and they cannot accept new applicants.

6.3 Retina Implant Alpha IMS, Germany

The most impressive surgeries and clinical trials with subretinal implants were run by the working group of Professor Eberhart Zrenner, Tubingen, Germany. The Retina Implant AG coordinates these trials. Many German clinics participate in this program, e.g., those in Regensburg, Dresden, and Kiel.

During the first phase of the trial running from 2005 to 2009 first generation implants were implanted into 11 patients. The second phase of the trial—with the participation of the Department of Ophthalmology Semmelweis University Budapest—provided evidence, that theoretically, the second-generation implants may remain in the human body for an indefinite time, because they are separated completely from the outside environment. Based on these results the second-generation subretinal prostheses achieved CE marking. The resolution of these devices is unique having as much as 1.500 pixels (Fig. 3).

The implantation of the chipset is done transchoroideally by the help of a special, supporting film. The exact position of the implant is specifically determined by previous considerations giving the promise of the best possible functional results (Fig. 3). The planning before the surgery includes the determination of the required place and the design of the wire with individual length [26]. Many preceding measurements including imaging processes and data analysis are needed for the precise chip and chip-location design [55]. At the operations so far no complications or side effects developed that would have required a further intervention. Subjects tolerated the surgery well and remained complaintless [56].

In several cases, patients having a successful implantation surgery told as if they had seen a shiny window frame. By the help of the prosthesis larger shapes became recognizable and changes in light intensity became distinguishable. The idea, that by the help of the subretinal implant a visual experience is achievable, was confirmed by the study of Tubingen in the most robust way of all. One of the patients had such a vision improvement that from a 60 cm distance became able to determine the direction of the Landolt C that is equal to a visual acuity of 20/1000 (log MAR = 1.69) [56]. A larger number of patients were successful in orientation tests; patients could recognize common subjects, like a plate, cutlery, a banana, etc [57].

The Alpha IMS has CE approval and currently commercially available in several European sites, at the moment testing of the updated model Alpha AMS is under investigation.

7 Orion I Visual Cortical Prosthesis (Orion I)

In October 2016, the Second Sight announced the first successful implantation of a wireless visual cortical stimulator in a human subject. The implantation was performed in the UCLA. The first implantation did not yet include a camera, but after the activation of the prosthesis, the young adult patient was able to perceive and localize individual phosphenes or spots of light. No any significant adverse side effect was observed.

8 Conclusions

Many preclinical and clinical trials of retinal, cortical and other vision restoration implants were started years ago and many are still in progress. The cortical, the subretinal, and the epiretinal prostheses have all reached the clinical phase. The outcome after the surgery depends on numerous factors. A comparison between the different types of implants and a summary of their differences would be useful.

If the electrodes are located the most physiological way, they may have an optimal use of the remaining neural cells able to process visual information starting at the first transmission step in the retina like in healthy functions. The intraretinal data processing has a great significance in the final visual experience. One of the most important advantages of the subretinal implant is the best possible use of most remaining functional cells and synapses. Since the subretinal implant is strongly attached to the retina the energy needed for the stimulation is lower, and the harmful heating effect is less. The retinotopic stimulation is beneficial too, because it is highly similar to the physiological signal transmission.

Moreover, the subretinal implant is fastened by the help of the intraocular pressure and does not require a rivet, like the epiretinal implant. As the subretinal implant does not touch the vitreoretinal surface, the proliferative-vitreoretinopathy, a severe complication is less likely to develop. Because the light sensors are on the surface of the Tubingen type chipset, with this approach exactly those retinal areas become stimulated, that the light falls on. This has two advantages: the exercises requiring coordination are easier to perform, and the fine eye movements are enough to position the subject in the focus not requiring large movements of the whole head to achieve this goal. Though further tests are needed to ascertain this statement, but from the experience gathered so far it seems that the micro-saccade movements of the eye play an important role in sensation of the sharp images and the contrasts. Therefore, this type of subretinal implant is able to refresh the neighboring pixels without further manipulation or programming.

Mobilization of the patients with visual loss is one of the most important goals of all the programs, and all the working groups handle the movement and coordination exercises carefully. As there are diverse tests for these functions, and no consensus exists among the groups, currently it is difficult to compare their results. Intentions emerge to develop a unified testing method enabling the direct comparison of the data of different working groups with different devices.

9 Future Trends

Retinal implants provide a promising chance for people having a vision loss with an intact visual pathway able to forward the generated signals of the chipset.

Developments in microelectronics in recent years made it possible and proved to be feasible to replace the degenerated elements in the retina with electrical stimulation. Multiple comparable approaches are running simultaneously. Two types of these implants are directly stimulating the remaining living cells in the retina. Hitherto the finest resolution has been achieved with the subretinal implants. Although the epiretinal implant offer lower resolution, but requires shorter surgery for implantation. Retinal implants in certain retinal diseases are proved to be capable of generating vision-like experiences. A number of types of retinal implants are already available in clinical practice.

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Mobility, Inclusion and Exclusion

M.A. Hersh

1 Introduction: Travel by Blind People

There are an estimated 285 million visually impaired people globally, with 39 million of them blind [1]. Nearly 10% of the estimated 1.1 million blind people in the USA use a long cane and just under 1% a guide dog [2]. Since these are the two most commonly used mobility devices, this implies that most blind people in the USA and probably the rest of the world do not use any mobility devices. A number of surveys have found that a significant minority of blind people do not leave the home (on their own) and that sole travel by blind people is generally local or restricted to known routes [3–6]. While these surveys are dated and some improvement may have occurred subsequently, there is still an urgent need for accessible environments and well-designed mobility aids to reduce the barriers to independent travel by blind people.

Mobility requires the analysis of sensory information to determine a direction of travel, avoid obstacles and walk in a (relatively) straight line. Unlike sighted people, who rely largely on vision for spatial information, blind people use information from all their senses with auditory and tactile information generally the most important. However, many partially sighted people are largely dependent on vision and people with progressive visual impairments may experience difficulties in adapting from vision based mobility to mobility based on all their senses [7]. Blind people use shore lines, such as kerbs, the edge of grass verges and walls, which are detected by the (long) cane rather than vision, to walk in a straight line. They generally require much greater concentration than sighted people when travelling

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and need to memorise route information to make up for the lack of overview and preview information available to them [7–9]. The need for memorisation and high levels of concentration impose a heavy cognitive load, making travel tiring for blind people. Additional information about the travel processes of blind people is provided in [10].

2 The Importance of Mobility for Participation in Society

In most industrialised/western countries car ownership and use has become the main form of transport and travel patterns have changed. For instance, people in the UK travel on average 10 times as far as they did 50 years ago, but it is average journey length, rather than the number of trips and time involved that has increased [11]. Increased car use has enabled the average person in many countries to carry out significantly more activities in a day and travel far greater distances than 50 years ago, but at a very high social and environmental price. It has led to significant disadvantage to people without car access and contributed to the further exclusion of already disadvantaged individuals and groups [12]. This is due to the changes in planning policy based on dispersed car-oriented development and an associated reduction in the availability, affordability and acceptability of public transport, as well as changes in the location of education, employment, healthcare, leisure and shopping facilities. There has also been a significant reduction in the quality of local environments [12–14].

Transport and land use policies in the UK have been found to systemically create and reinforce social exclusion [15] and the same is highly likely to be true elsewhere. In particular, not having a car can be a significant barrier to obtaining employment and restrict job choice by making it more difficult to travel to interviews and the workplace. It also makes it more difficult to participate in post-16 education and training, attend hospital appointments, get to leisure facilities and reasonably priced food shops and visit family and friends [14]. Therefore, many non-car owners have reduced access to services, facilities and social networks [14]. This is particularly problematical for blind people who are rarely car drivers and generally require public transport to go anywhere they cannot reach on foot. In rural areas the lack of public transport can make access to most facilities, which are generally located in the nearest town, very difficult [16]. This combination of a lack of transport and things to do locally can act as a disincentive to blind people in rural areas going out on their own. As one of my research participants said ‘I do not go about on my own. … It is a little village… there’s nothing there, not like a town with shops’ [17]. Demographic changes with an ageing population also increase the need for public transport to avoid further exclusion. Many people cease driving as they get older. In addition there is a cohort of particularly older women who have never driven and are likely to outlive any male partners who may be drivers.

Public transport is frequently (relatively) good in large cities, leading to reduced car ownership. However, it is not necessarily fully accessible or easy to use by blind and other disabled people. Travel information is rarely fully accessible. For instance, arrivals and departures boards in stations are frequently located too high up (above eye level) to be read by partially sighted people. They do not have an audio equivalent, for instance an audio announcement when a button on a pole in an easily identifiable location is pressed. Although the use of audio bus stop announcements is increasing, they are not universally available and not always clear. Accessible information on the numbers and destinations of arriving buses is rarely available. However, an audio announcement system operated by remote control has been in use in the Czech Republic for a number of years [18]. Buses frequently arrive in groups and do not stop long enough for blind people to ask the driver or another passenger the bus number or destination [19]. Public transport needs to be both accessible and available when people want to travel [20]. Even when public transport availability is relative good during the day it is generally much poorer at night, making it more difficult for blind and other public transport users to visit family and friends and participate in other social activities or work or study at night.

In addition to the factors already discussed, including availability, service location and cost, concerns about safety and security when travelling and unwillingness or lack of confidence to travel any distance from home can act as barriers to the use of public transport [15]. Blind people experience various barriers to travelling on their own and in some cases may find it difficult or lack the confidence to travel even relatively short distances. In addition to normal safety concerns, there is also some risk of hate crimes or other forms of violence. My research shows some evidence of targeting of cane users [17] and particular safety concerns by blind women [19].

2.1 Approaches to Improving Public Transport

Measures are required to improve public transport, both in general and for specific groups, such as blind people. This could include prescribed minimum accessibility levels, such as the percentage of people in an area who live within a 10 minute walk of an hourly or better bus service [21]. However, although this could lead to improvements, some people would still remain excluded, including people for whom a 10 minute walk is a barrier. In addition, minimum levels easily become maxima. Accessibility planning has some potential, but should be accompanied by measures to restrain and significantly reduce exponential growth in car travel [12].

Changes in the way in which public transport is financed and paid for can also have an impact. I would suggest that it should be treated as a public service financed totally from taxation and free at the point of use rather than as a commodity to be paid for by users. This would have a number of advantages. In particular, it would remove the barrier of frequently high cost to the use of public transport and allow more equal or at least considerably improved provision, particularly in rural areas, where subsidies would otherwise be required to allow fare reductions. Free public transport could also have a positive environmental impact, by encouraging a modal shift from private car use to public transport. However, it may need to be combined with a public relations campaign to improve the image of public transport. Improvements in quality and comfort and, in some cases, punctuality and integration between different types of public transport will also be required.

There have been a number of initiatives to improve public transport, particularly for members of marginalised groups, and most of them seem to have had a positive impact on users by increasing access to services to some extent. However, they have generally had local rather than national coverage and not always included sufficient features [22]. They have included personal training schemes, dial-a-ride and community transport schemes for disabled and older people of rural areas, improved public transport and walking and cycling routes.

It can be useful to have a framework for the improvement of public transport for blind and other groups of disabled people. One possible approach is based on eight different concepts that have been identified in the literature on geographical equality, justice and fairness and which can be divided into the two groups of justice, equity and equality concepts and deserts, rights and needs [23]. In the case of access to transport and facilities for blind and other groups of disabled people, rights, needs and 'substantive equality' of outcomes are probably the most useful concepts. A framework based on rights, needs and outcomes is particularly useful, as it implies that blind people are entitled to be able to access public transport and other facilities that meet their needs and that this will require specific consideration of what these needs are and what is required to ensure they are met. It also avoids marginalisation by providing a context in which blind people are one of a number of groups who require specific provisions for their needs to be appropriately met and implies that a tick box approach is not sufficient.

2.2 The Private Car—Glamour and Exclusion

Various factors influence the value of a particular possession, including its usefulness, the associated enjoyment, its symbolisation of social relationships and its role in expressing and/or reinforcing identity and self-expression [24]. Several studies show that that people buy and drive cars as a source of pleasure rather than purely in response to need [25]. Car use is evaluated positively on instrumental, symbolic and affective features, whereas public transport is judged much less positively [26, 27] and even survey respondents who rarely used their car have been found to prefer it to public transport on most features [27]. The level of car use and, in particular, car commuting has been found to be generally determined by symbolic and affective rather than instrumental motives [28], with the car being considered a status symbol and means of expression by many people [29]. Frequent drivers have been found to evaluate the symbolic, but not the affective function of car use more favourably than infrequent drivers [28].

However, large scale car use also causes serious problems. The impact on development planning and reducing the availability and quality of public transport has already been discussed. Globally it is a major energy consumer and contributes to global warning whereas locally it causes air pollution and health problems. Noise, traffic accidents and land encroachment have reduced the quality of life in urban areas [29]. Land encroachment, due to, for instance a car requiring 24 times as much road space per person as a bus [30], has led to a reduction in the historical/cultural, aesthetic and restorative qualities of urban areas, leading to a reduced quality of life. The associated congestion has reduced accessibility to various destinations [29] for non-car users as well as car users. The prevalence of affective and symbolic over instrumental motives in car use shows both that car use is by no means essential and the likely opposition and difficulties in reducing it.

In the case of blind people with progressive visual impairments giving up driving is a marker of increasing visual impairment which is strongly resisted. According to one of my research participants ‘I had normal vision for a long time, I drove a car. I received a diagnosis, but you resist it,… you continue driving, though with difficulty…. I had a small accident and then I stopped driving’. For blind people the issue is probably as much the symbolic and emotional significance of being able to drive as its practical usefulness. Thus giving up driving when changes in vision make it no longer safe is not easy, since it requires acceptance of disability and change of status to a person who is no longer able to drive.

3 Attitudes to Blind People

There has been some work on the development of attitudes to and social responsibility about blindness scales, e.g. [31–33]. However, even the existence of such scales is an indicator of a potential problem or the fact that blind people are a minority group that requires particular consideration. There do not seem to be any attitudes to or social responsibility to sightedness scales, probably because sightedness is seen as the ‘norm’, making consideration of attitudes to it apparently unnecessary. Positive attitudes to oneself and one’s identity groups are generally beneficial and can have a positive impact on learning, whereas negative attitudes can have the opposite effect. This is a particular issue in the case of blind people, where stigma about blindness and the (long) cane can affect cane use [17].

Studies have found that blind people have more positive attitudes to blindness than sighted people and women have slightly more positive attitudes than men, though the gender difference may not be large enough to be meaningful [33, 34]. In addition, previous contact with blind people has generally been found to improve attitudes [34]. Thus, personal knowledge may be sufficient to overcome stereotypes and misconceptions. However, this effect has been found to be slightly reduced for people with a blind person in their family, possibly as a result of contact with relatives who became blind later in life, but did not become independent as a blind person [34], but this would need to be investigated.

3.1 Stigma and Stereotypes

The term stigma may originate in the abusive practice of the ancient Greeks of cutting, burning or branding slaves, traitors and offenders [35]. However, there is still not a generally accepted definition. Work by Goffman [35] was influential, but has been extensively criticised for its outdated and inappropriate concepts which are incompatible with multicultural and pluralist societies [36]. A fairly comprehensive recent definition [37] involves distinguishing and labelling salient differences, e.g. gender and disability which lead to negative attributes or stereotypes, the separation of dominant ingroups ('us') and stigmatised outgroups ('them') and consequent status loss and discrimination. Both individual and group discrimination occur [38].

Stigma can act at the level of large groups (social), structural systems and individuals (internalised) [38]. The endorsement of stigma or stereotypes by large groups can lead to the use of stigmatising labels, ostracism, discrimination and violence. This stigma can also affect the friends, family and close associates of stigmatised individuals, in this case called courtesy stigma [35]. Structural stigma results from the rules, policies or procedures of organisations which result in discrimination and disadvantage for stigmatised groups, e.g. institutionalised sexism, racism and ablism. Internalised stigma can result in reduced self-esteem, self-efficacy, empowerment and morale and a lower quality of life [39]. It can lead to individuals restricting their own opportunities and life chances by not, for instance, applying for a particular job due to stereotypical beliefs about their (lack of) abilities as members of a particular group. As will be discussed later, it can also lead to rejection of assistive devices, such as the (long) cane [38], with a resulting reduction in travel safety and/or opportunities. Differences in power are an important, but neglected, feature of stigma, with stigma generally affecting only relatively powerless groups [38], such as blind people. Stigma can also increase existing inequalities resulting from factors such as gender and income [40]. It is a consequence of group membership, but individual members of stigmatised groups may have very different experiences and use very different strategies to deal with it.

Like many social phenomena, stigma is a construct rather than something innate. Consequently, different societies frequently have different attitudes to stigmatised groups, including disabled people, and assistive devices. However, cross-cultural comparisons have generally focused on the attitudes of non-disabled people [41–43] or the experiences, including of courtesy stigma, of the parents of disabled children [44, 45] rather than those of disabled people.

The identification of patterns and the use of categorisations [46] can be a very helpful mental tactic for organising information, recognising similarities and reducing cognitive load. Unfortunately, these approaches can also lead to stereotypes [47], which may act as self-fulfilling prophecies. Other causes of stereotyping are discussed in [48]. Even apparently positive stereotypes, related for instance to the stereotypical talents of a particular group, can be damaging and should be avoided. They are based on false assumptions of greater homogeneity of minority than majority groups and can reduce the opportunities available to members of these groups, for instance in employment through stereotypical assumptions about their abilities and what jobs are suitable for them. In addition, stereotyping easily leads to minority groups being perceived as ‘other’ and acts as a barrier to inclusion [47]. There are probably individuals, both blind and sighted, who meet particular stereotypes. However, this is not the issue. The problem is rather assuming that particular stereotypes, whether positive or negative, are valid for the (overwhelming) majority of blind people.

Stereotype threat involves concerns about negative perceptions resulting from group membership. It has been found to lead to reductions in short-term performance. Long-term stereotype threat can lead to reduced feelings of self-integrity and adaptive adequacy and may result in reduced motivation, performance and well-being [49]. Fear of stereotyping or stereotype threat can lead to avoidance of situations, such as job applications or learning to use a long cane, in which stereotyping is likely to occur in order to preserve a self-image of adaptive adequacy. This has been found to reduce well-being, employment and challenge seeking and increase global stress. However, there is also some evidence that value affirmation can reduce the impacts of stereotype threat [49].

Older surveys e.g. [50] indicate three main stereotypes of blind people, namely that they deserve sympathy and pity, are either totally incapable or have extraordinary non-visual senses and all share similar interests, as well as indications of the effectiveness of educational interventions in changing these stereotypes. However, further research will be required to investigate whether these stereotypes are still current and any changes in the types and prevalence of stereotypes over time.

The representation of blind and other disabled people in literature and the arts is indicative of attitudes to them. Unfortunately stereotypes of dependency, helplessness and infantalisation and the appropriation of the blind gaze to maintain the dominant position of sighted people are common, for instance in the representationsof blind women in the cinema [51]. Some English language literature has apparently positive stereotypes based on the concept of ‘beneficial blindness’. However, this can be just as damaging as more obviously negative stereotypes. Stereotypes of ‘beneficial blindness’ diminish the achievements and talents of blind people [52] and trivialise the often very serious barriers they have to overcome.

‘Positive’ stereotypes of blindness include musical genius, ‘effortless success’ and possessing extraordinarily sensitive non-visual senses [52]. The stereotype of effortless success is based on the assumption of an increased ability to concentrate due to the lack of (visual) distractions. This implies that vision is the only important sense and downgrades the value and interest of information from the other senses. While independent travel (with a cane and other travel aids) does require very high levels of concentration, there is no evidence that blind people have a greater ability to concentrate than sighted people in general. Research indicates that the senses of blind and sighted people are comparable [53] and that blind people who use their other senses more effectively do so as the result of practice rather than automatically [54]. Thus, beliefs that blind people have extraordinary senses are purely stereotypes with no basis in reality. There are also a number of negative stereotypes in fiction, including a confusion of dreaming and waking and a lack of knowledge about the world about them [52]. These stereotypes are in direct contradiction to the 'positive' stereotypes of a superior ability to concentrate and non-visual senses. This further illustrates the total lack of logic and connection to reality of stereotypes.

3.2 Acceptance and Confidence

Calls have been made, e.g. [55] for the acceptance of diverse ways of doing things in public spaces. This would be relevant to ethnic and other minority groups, as well as disabled people, since it would cover the use of different languages, dialects, greetings and other rituals, as well as types of dress and food. It would also lead to recognition that there are different types of mobility and lead to equal indifference to or acceptance of, for instance, long cane and GPS use and mobility scooters and electric cars. In practice, we are a long way from this situation of equal acceptance of mobility with and without assistive devices and indifference to whether or not people use assistive devices to support travel. This would require a very significant change in attitudes to disability and disabled people.

The potential additional accomplishments of disabled people if they did not have to cope with negative attitudes, inaccessible environments and feeling that they are 'on approval' have been noted [55]. In particular, for blind people the ability to use mobility devices without having to worry about other people's attitudes and people 'staring' [17] could be both liberating and significantly increase their freedom of movement and social participation. However, this would not remove the need for design to take into account device appearance. Attractive device appearance, compact size and weight and easy portability are important design features in themselves and not just a way to reduce the stigma associated with device use.

A lack of confidence has already been indicated as one of the barriers to travel using public transport. Some of my research participants lacked the confidence to travel on their own with a cane and preferred to use a sighted guide. Travelling on their own was a particular issue for deafblind people who face additional barriers due to communication difficulties [19]. There may also be a gender dimension to the lack of confidence. While by no means the most frequent occurrence, my Italian respondents included a few blind and/or partially sighted couples where the blind or partially sighted woman did not use a cane, but her male partner did and served as her guide. This included partially sighted women with blind partners, in which case cane use resulted in the male partners having a much greater degree of independent mobility despite their greater visual impairments [56].

The role of cane use in increasing independence and opportunities together with the desire for independence and participation can act as important motivating factors to overcome the barriers to (effective) cane use. The limited availability of sighted guides may also force people to accept the cane, though the comments of a number of my research participants indicate that they found being accompanied less stigmatising. Support, including from other blind people and instructors, was found to be very helpful in overcoming the barriers to cane use [17].

4 Stigma and the Use of Mobility Technology

Since the long cane is the most commonly used mobility device it will be the focus of this section. The cane is commonly used as a symbolic representation of blindness and blind people [57]. Since blindness is unfortunately still a stigmatised identity this makes the cane a 'visible stigma' of blindness [58]. This identification can become a reason not to use the cane, as it forces users to confront and come to terms with the fact that they are blind or partially sighted [38], and consequently people who do not (fully) accept their visual impairment may delay or never even start using a cane. As stated by one of my respondents who became blind in later life 'the cane is a symbol that I am blind and cannot hide it any more'. This symbolic identification and 'visual stigma' may be largely responsible for the self-consciousness, worries about being stared at and consequent aversion to cane use reported by many of my interviewees [17].

The symbolic identification of the cane with blindness means that the cane may be seen as only for totally blind people, leading to some partially sighted people, newly blind people and people with progressive conditions finding it difficult to accept or delaying cane use [58]. For instance, one of my respondents 'delayed a lot in using a cane as, as long as I had some vision, … I could get about normally' [17]. One of my research participants who used several assistive devices considered the long cane the most difficult to accept. 'It's difficult to accept because it has to work with the invisible signs of disability … You actually have to accept the new visual images of yourself. You have to accept your mirror image and integrate it into yourself' [38].

The long cane is intended to be easily visible and to attract attention in order to alert pedestrians and road users to the fact that the user is blind or partially sighted and encourage them to be particularly careful around the user, as well as making it easier for the user to obtain assistance when required. However, this visibility frustrates the desires of many potential users to be inconspicuous and not draw attention to their visual impairment. Despite recognition in the disability literature of this value of interdependence, e.g. [59] and the role of autonomy or making choices and having control over one's life [60, 61], the need to be independent in the sense of doing everything oneself is still predominant in western industrialised societies. In practice, almost everyone in modern industrialised societies is dependent on other people and very few, if any, people are totally self-sufficient. However, the persistence of the value judgement can make it difficult to accept the need for assistance. In the words of one of my interviewees 'It's difficult, possibly because [using a cane] makes it apparent to other people that you need help' [17].

Shame, embarrassment and not wanting to ‘stand out’ and ‘be marked as the blind person’ act as particular barriers to starting cane use [17, 62]. Research participants with progressive visual impairments or who became blind later in life were often concerned about what people who knew them before they started using a cane would think or found that other people experienced difficulties in accepting that they really were blind [17]. In some cases they even travelled away from home to learn to use the cane or found it easier to use it in areas where they were not known. Delays in starting cane use as a result of these concerns were relatively common. In a number of cases it took one or more accidents to convince blind and partially sighted people of the need to use a cane for their own safety [17].

Feelings of shame and embarrassment may also lead to attempts to use a cane while trying to hide it, for instance by having the cane folded or using a short cane, making cane use either less effective or totally ineffective [17]. Some blind people, for instance those with night blindness, do not need a cane all the time. However, rather than taking a folded cane with them so they could use it when necessary, they frequently did not use it at all, even when it was definitely necessary. In some cases it is friends and relatives who are ashamed of the cane [17], probably due to the negative views of disability and disabled people that still have not been eradicated [63] and possibly due to fears of courtesy stigma [35]. Consequently some regular cane users do not use a cane when visiting these friends and relatives [17]. However, support and encouragement from family and friends can be important in overcoming the barriers to cane use and supporting blind people through the extended training and practice required to learn to use a (long) cane effectively and safely. On the other hand, active discouragement and disapproval can have the opposite effect and negative attitudes, lack of acceptance and stereotypes generally reduce confidence, self-image and self-esteem [38].

It is only relatively recently that attention has been given to the appearance of assistive devices [64], though this is important to end-users, who want devices to be elegant and attractive [65, 66]. In some cases end-users may have been expected to be grateful for the availability of any devices regardless of whether they are stigmatising [64]. The fact that blind people sometimes need sighted friends to point out that devices are not attractive [62] is not a valid reason for unattractive device design. Functionality and appearance need to be appropriately combined [67] to produce attractive, effective and high performance mobility (and other) devices with functions that meet users’ needs. Unsurprisingly blind people have been found to frequently share the general preference for small easily portable devices, such as mobile and smart phones, rather than larger, more awkward and less easily portable devices. Thus, mobility apps on mobile and smart phones are popular with many blind and partially sighted people and have the advantages of looking like devices that everyone uses and therefore being non-stigmatising, in addition to easy portability. Device design should enable similar items or features to be easily distinguished to improve usability [68]. However, designing a mobility app which is able to provide basic obstacle avoidance features may be difficult.

5 Accessible Environments

Appropriate design and the provision of navigation and information systems can considerably improve the accessibility of urban environments, generally with considerable benefits for both non-disabled people and blind and other disabled people. Designers, planners and architects should be educated in the principles of accessible environmental design [69]. They should also regularly consult with (organisations of) blind, partially sighted, deafblind and other disabled people and involve them in any proposals for environmental modifications.

Geographical data is very helpful in supporting mobility. Geographical information systems (GIS) are generally accepted to be an important tool for storing, manipulating, representing and analysing spatial information. GIS software has enabled sighted people to view spatial data and made it easier to understand [70]. However, the visual formats frequently used to represent this data make it inaccessible to blind people, giving a need for accessible versions.

The following principles of accessible design are based on [69].

Lighting and surfaces

1. Good illumination of all public and pedestrian areas, generally using diffuse rather than direct lighting and taking care to avoid shadows. As far as possible, a choice of lighting types and the facility to regulate lighting levels should be provided in all rooms in public buildings.
2. Matte surfaces to reduce glare.

Signage and information systems

3. Well-designed signage systems, covering both directional information, e.g. to the nearest station or toilets and location information, e.g. a sign on the door of a particular room or public building. Whenever feasible, the information should be given in tactile, visual and audio form.
4. Tactile paving to warn of hazards and direct people to facilities.
5. Colour contrasts, including colour contrasting strips, to provide information and make it easier for blind and visually impaired people to distinguish, for instance, door handles and furniture.

Safety

6. Wide pathways which can accommodate wheelchair users and blind people with guide dogs, a sighted guide or a guide-communicator in the case of deafblind people.
7. Good layout design so that facilities, such as benches, litter bins and furniture, do not become potentially hazardous obstacles.
8. Regular maintenance programmes to prevent avoidable hazards such as holes in the road, due to the poor state of building and streetscape repair.
9. Two supports for all signs on the pavement to facilitate detection with a cane and reduce the risk of accidents to (deaf)blind people. Care should be taken to

ensure that signs do not block the pavement and temporary signs should generally be put at the side of the road rather than on the pavement.

10. Appropriate location of bus stops, preferably widening the pavement if necessary, to provide sufficient space for wheelchair users and (deaf)blind people with guide dogs, a sighted guide or a guide-communicator.
11. Frequent and appropriately located cycle parking to avoid bikes being chained to lamp posts or the poles of accessible crossing indicators/traffic lights and becoming a potential hazard.

Public awareness

12. Publicity campaigns to increasing awareness of the needs of disabled pedestrians, including to reduce street furniture, particularly on (relatively) narrow pavements, and their ability and right to travel on their own.

5.1 Public Transport

(Deaf)blind people require accessible and widely available public transport to travel outside the areas they can reach on foot [38]. Public transport therefore needs to become more widely available in regards to both times and location and also more accessible. This will require increasing the frequency of all forms of public transport, extending coverage to villages and areas of towns with only limited services and extending the hours of service into the night and early hours of the morning. Access to information is an important feature of accessibility. This should include both audio announcements and tactile information of the approaching bus stop and the number and destination of approaching buses.

Audio announcements should be clear, pleasantly modulated and an appropriate volume. They need to be sufficiently loud to be easily heard, but not excessively loud to avoid causing irritation. In the case of stations with a two word name both need to be pronounced clearly rather than the first word clearly enunciated and the second muttered. However, there is still the question as to whether the announcements should be always on or operated by a mobile or smart phone app or remote control. Constantly on announcements would be (potentially) available to all travellers, but could irritate the driver and autistic and some other travellers. Announcements turned on by an app or remote control would avoid noise disturbance and the driver turning the announcements off, but would require users to have the app or remote control.

Existing systems, for instance in the Czech Republic, for obtaining an audio announcement of the bus number and destination through the use of a remote control should become generally available. However, some improvements in voice quality and volume control will be required, as well as the option for receiving the information via an ear piece. In addition, technological developments mean that apps on smart and mobile phones are now more appropriate for many, though not all potential users. Other strategies which should become better known and generally accepted include the use of plastic cards with the bus number as an indication for the bus driver to stop, with colour coding to indicate whether the person is blind or deafblind. Requiring all buses to stop briefly at the head of the queue, particularly when several arrive together, would give (deaf)blind people time to obtain information to identify the number and enable all slower moving users to get to the bus and get on in time.

Another important issue is training. All transport personnel should have disability equality training (organised and provided by disabled people) as well as training in interacting with and meeting the needs of particular groups of disabled people. This training should also be updated on a regular basis.

5.2 Accessible Pedestrian Crossings

Crossing the road safely is an important issue for all pedestrians and raises particular issues for several groups of pedestrians, including (deaf)blind and some other disabled people, people who move slowly and children. The widespread use of accessible pedestrian crossings could resolve many of the crossing problems experienced by (deaf)blind people. Major roads can act as a barrier to unaccompanied travel by blind people and to an even greater extent to deafblind people: the strategies commonly used by blind people of using their hearing to decide when to cross, asking for assistance and crossing with other people may not be feasible for deafblind people The availability of accessible crossing indicators is essential to overcome these barriers and support unaccompanied travel by (deaf)blind people. It also has the further advantage of enabling (deaf)blind people to cross without requiring assistance, which is of value both in itself and because there may not be other people available to provide it.

Deafblind people require vibro-tactile crossing indicators, whereas blind people can use either audio or vibro-tactile indicators, but tend to prefer audio signals. Traffic crossing indicators (traffic lights) with audio signals are more common than those with tactile signals, though neither is particularly widely available. There is considerable variation in the design of audio signals. This includes the types of audio signals used for the crossing and waiting phases, whether the signal is continuous or initiated or made louder by a remote control and whether it is located on poles on one or both sides of the road or on a small loudspeaker on the remote control. In the vibro-tactile case, vibration or other movement is used to indicate the crossing phase of the signal, but there are considerable differences in the design and location of the vibrating or other moving component. The differences n audio signal used could result in real danger to users, particularly as the same signal may be used to indicate the waiting and crossing phases on different designs.

In the case of deafblind people research [19] indicates the need of an international standard for accessible crossing points. In addition to a standard design of vibro-tactile crossing indicators, they should also include tactile arrows to facilitate alignment with the crossing direction and tactile tiles to indicate the best straight path across the road. In the case of blind people further research is required to develop a standard for accessible audio signals and incorporate it into the accessible crossing standard. Analogous considerations as in the case of bus stop announcements hold with regard to whether the standard should involve constantly on signals or signals operated or made louder by an app or remote control. The fact that different crossing and waiting audio signal are already in use in different places will complicate the decision on a standard and its acceptance and incorporation into all crossings. Building a considerable number of additional crossings to this standard and upgrading existing crossings on a phased basis would improve safety for deaf (blind) people and other groups, including children, and facilitate travel to other cities and countries by (deaf)blind people.

Roundabouts should as far as possible be replaced by road junctions with crossing points with standardised accessible pedestrian signals. Changing regulations, where necessary, to forbid turning on the crossing phase of crossing indicators would increase safety for both blind and many groups of disabled people and people from countries where this is not allowed [19].

6 Discussion and Conclusions

Everyone, whether disabled or not, should have an equal right to participate in and contribute to society in all its aspects. Development is increasingly based on the needs of car users rather than pedestrians and public transport users. This has led to increasingly dispersed developments and frequently the need to travel longer distances in order to access employment, education, leisure and other facilities, while in many areas public transport has reduced. Even where public transport is relatively good, it is often not fully accessible to blind and other groups of disabled people. In the case of blind people one of the main barriers is the lack of fully accessible information. Public transport availability is particularly limited in rural areas, but most facilities are located in towns which may therefore be difficult to impossible to reach without a private car. The solutions need to cover both increased availability and quality of public transport with regard to routes and times covered and accessible information. Some of the potential solutions have been discussed in the chapter.

Apps on mobile and smart phones have particular potential to provide accessible information to blind and partially sighted people and to some extent also to deafblind people. Mobility support apps are equally relevant to disabled and non-disabled people, particularly in unfamiliar, complex and unstructured environments. However, obstacle avoidance functions are particularly useful to blind, partially sighted and some other groups of disabled travellers, whereas personalised and contextual travel advice and information, route planning, navigation and wayfinding, locating facilities and travel timetables are equally relevant to all travellers. Blind people frequently require more detailed and additional information compared to non-disabled travellers to enable them to travel safely and effectively. This could usefully include the location of bus stops and pedestrian crossings, as well as time sensitive and other contextual features such as roadworks and when cafes are open and likely to have tables on the pavement.

Mobility devices both have an important role in supporting mobility and are a potential source of stigma and attention to the user as a disabled person. Particular issues are raised by the (long) cane which, as a symbol of blindness confronts the user with their visual impairment. This forces them to either 'integrate it into yourself' in the words of one of my research participants [38] or leads to rejection and non-use, at least initially. Many blind and partially sighted people prefer to travel accompanied than use a long cane, due to varying combinations of shame and embarrassment about cane use and concerns about the difficulties and danger involved in unaccompanied travel. However, the downside of this is a degree of dependence on other people and some restrictions on mobility, since another person is not always available to accompany them. In other cases accidents force blind and partially sighted people trying to travel on their own without a cane to accept it in the interests of safety.

Improved device design to be attractive, unobtrusive and resemble devices used by non-disabled people can resolve some of the problems. However, the long cane in particular has the supplementary function of marking the user as a blind person, thereby facilitating them obtaining Assistance and encouraging other people to take particular care round them. A totally unobtrusive device would be unable to fulfil this function. There is thus a need to challenge and overcome stereotypes and negative attitudes to blind people both because of the value of doing this in itself and to overcome barriers to using mobility devices which can be 'positively liberating' due to the removal of dependence and the need to be accompanied everywhere [71].

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