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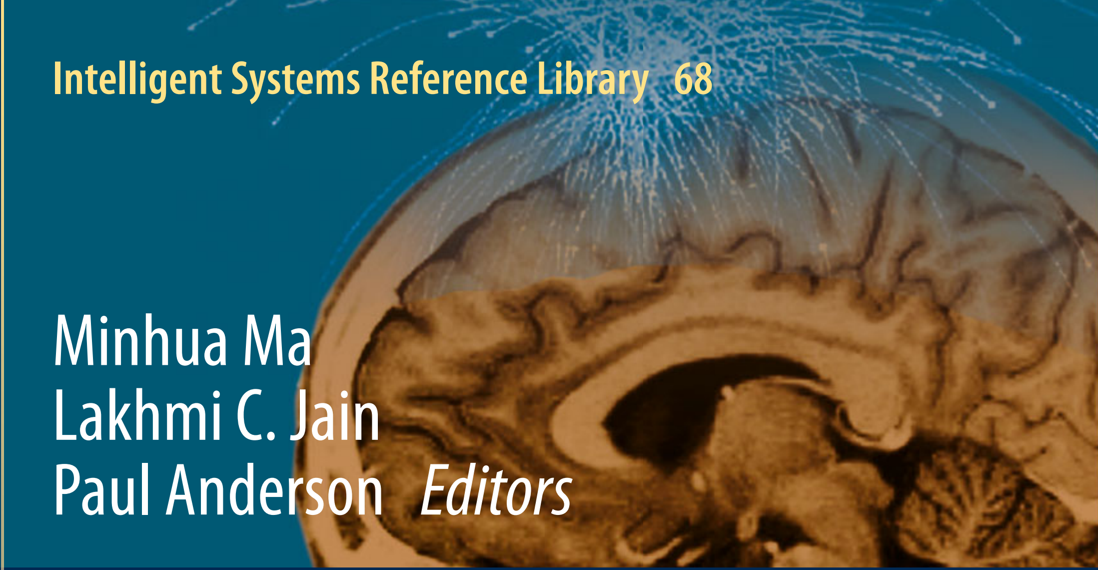

Minhua Ma
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Virtual, Augmented Reality and Serious Games for Healthcare 1

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Preface

There is a tremendous interest among researchers for the development of virtual, augmented reality and games technologies due to their widespread applications in medicine and healthcare. To date the major applications of these technologies include medical simulation, telemedicine, medical and healthcare training, pain control, visualisation aid for surgery, rehabilitation in cases such as stroke, phobia, trauma therapies and addictive behaviours. Many recent studies have identified the benefits of using Virtual Reality, Augmented Reality or serious games in a variety of medical applications.

This research volume on *Virtual, Augmented Reality and Serious Games for Healthcare 1* offers an insightful introduction to the development and applications of virtual and augmented reality and digital games technologies in medical and clinical settings and healthcare in general. It is divided into six parts. Part I presents a selection of applications in medical education and management using virtual, augmented reality and visualisation techniques. Part II relates to nursing training, health literacy and healthy behaviour. Part III presents the applications of Virtual Reality in neuropsychology. Part IV includes a selection of applications in motor rehabilitation. Part V is aimed at therapeutic games for various diseases. The final part presents the applications of Virtual Reality in healing and restoration.

This book is directed to healthcare professionals, scientists, researchers, professors and undergraduate/postgraduate students who wish to explore the applications of virtual, augmented reality and serious games in healthcare further.

We thank the authors and reviewers for their contributions. The assistance provided by the editorial team of Springer-Verlag is acknowledged.

Minhua Ma
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Part V Therapeutic Games Aimed at Various Diseases

Chapter 1
Future Trends of Virtual, Augmented Reality, and Games for Health

Minhua Ma, Lakhmi C. Jain and Paul Anderson

Abstract Serious game is now a multi-billion dollar industry and is still growing steadily in many sectors. As a major subset of serious games, designing and developing Virtual Reality (VR), Augmented Reality (AR), and serious games or adopting off-the-shelf games to support medical education, rehabilitation, or promote health has become a promising frontier in the healthcare sector since 2004, because games technology is inexpensive, widely available, fun and entertaining for people of all ages, with various health conditions and different sensory, motor, and cognitive capabilities. In this chapter, we provide the reader an overview of the book with a perspective of future trends of VR, AR simulation and serious games for healthcare.

1.1 Introduction

The recent re-emergence of serious games as a branch of video games has introduced the concept of games designed for a serious purpose other than pure entertainment. To date the serious games industry is a multi-billion dollar industry and is still growing steadily in many sectors [1] including education and training [2, 3, 4, 5], healthcare [6, 7, 8, 9], engineering [10], military applications, city planning, production, crisis response, just to name a few. Serious games have primarily been used as a tool that gives players a novel way to interact with games in order to learn skills and knowledge, promote physical activities, support social-emotional development, and

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treat different types of psychological and physical disorders amongst others. Many recent studies have identified the benefits of using video games in a variety of serious—even critical—contexts. Games technology is inexpensive, widely available, fun and entertaining for people of all ages, with various health conditions and different sensory, motor, and cognitive capabilities. If utilised alongside, or combined with conventional educational or therapeutic approaches it could provide a more powerful means of knowledge/skill transfer, promoting healthy behaviours, restoration and rehabilitation.

This book *Virtual, Augmented Reality and Serious Games for Healthcare 1* offers an insightful introduction to the development and applications of games technologies in healthcare settings. It includes cutting edge academic research and industry updates that will inform readers of current and future advances in the area. The book is suitable for both researchers and healthcare workers who are interested in using games for medical education and rehabilitation, as well as game professionals who are trying to gain a thorough understanding of issues involved in the application of VR, AR, and games technology into the healthcare sector.

1.2 Chapters Included in the Book

This book includes 26 chapters. Chapter 1 provides an introduction to serious games and VR, AR simulation for healthcare. It presents brief abstracts of all chapters included in the book. The book is divided into six parts: *Applications in Healthcare Education*, *Nursing Training and Promoting Healthy Behaviours*, *Applications in Neuropsychology*, *Applications in Motor Rehabilitation*, *Therapeutic Games aimed at Various Diseases*, and *Virtual Healing*.

Part one includes six chapters that present various VR simulations and serious games applications in medical education and healthcare training. Chapter 2 applies educational theories in using VR simulations and serious games for healthcare training enhancement, and suggests how to assess their value within an educational context. The authors categorise training tasks based on levels of abstraction: from kinematic and dynamic aspects to higher knowledge level of reasoning, planning, and assessment. They describe a framework for evaluation of speed and accuracy of these multi-level tasks in order to validate the effectiveness of VR simulations before inclusion in medical curricula. Chapter 3 presents a haptic-based VR head and neck model for teaching human anatomy and dental training that focuses on sensori-motor dynamical and kinematic skills. Chapter 4 reviews recent human computer interaction techniques in visualising molecular and structural biology for education and research. VR interactions range from spatial manipulation to sensory perception of biological reactions. This is named *in virtuo* analysis, which provides many benefits comparing traditional in vivo, in vitro, and in silico approaches. In Chap. 5, a volumetric visualisation system of heart from cardiac magnetic resonance imaging is presented. The system features Kinect-based gesture recognition, 3D holographic display, and sonic feedback, and it also visualises the blood flow through the heart revealing the functionality of cardiovascular circular system, which is critical for medical education. Chapters 6 and 7 discuss the challenges of adopting e-health services and disruptive innovation in the healthcare sector, from the management and governance perspective, and how visualisation technologies can support sustainable healthcare.

Part two covers the use of VR and games for nursing training, improving health literacy, and promoting healthy behaviours. Chapter 8 provides a comprehensive overview with emphasis on community health nursing, which differs from that of a nurse clinician. Traditional nursing education that focuses on individual patient care in hospitals may not suitable for community health nurses. VR simulation and serious gaming provide a viable, cost-effective, and interactive environment for community health nursing trainees. Both Chaps. 9 and 10 present a number of virtual worlds in Second Life, e.g. the Nightingale Isle, which facilitates medical simulations and ambulatory care role-play experiences etc. to support nursing students; the HealthInfo Island where users can play games to improve health information literacy on topics of heart attack, stroke, and medical terminology.

The applications of VR and serious gaming in promoting healthy behaviours are discussed in Chaps. 11 and 12. Chapter 11 proposes a novel approach that aims to design exergames which interact with the player's built, topographic, and social environment in a meaningful way and presents strategies on how to integrate research on health-oriented urban design and planning to the design of exergames. The authors also discuss potential health benefit of location-based games, such as *Zombies Run* and Google's *Ingress*, which are more addictive due to the connection of the game elements with the real world. They encourage players' physical activity such as walking, running, and cycling during game play. As obesity and lack of physical activities become a growing problem of our society, this type of exergames have lots of potentials to engage people into light or moderate physical activities. Chapter 12 presents findings on how and to what extent rewards and incentives in exergames are persuasive and compelling to entice players in adhering to the game over time using the game statistics of *SpaPlay*, an online social game designed to motivate players to adhere to healthy eating and exercising behaviours.

Part three includes three chapters on the topic of VR applications in neuropsychology. Both Chaps. 13 and 14 focus on neuropsychological assessment. In Chap. 13, the authors argue that traditional neuropsychological tests lack ecological validity and it is controversial to generalise the results to describe individuals' daily life cognitive functioning. Virtual reality technology provides a more objective, precise, and ecologically valid approach to neuropsychological assessment. They also review the progress made in using VR-based tools to measure cognitive functions such as attention, memory or executive functions. Particularly, Chaps. 14 and 15 elaborate the characteristics of the Virtual Multiple Errands Test (VMET), a VR simulation developed using NeuroVR—a free virtual reality platform for assessment and neuro-rehabilitation.

The next part provides an overview and individual case studies of VR and games applications in motor rehabilitation, especially post-stroke rehabilitation. Chapter 16 presents the European project REWIRE that provides a broad architecture involving patients, therapists, clinicians, hospitals and health providers for motor rehabilitation at home. The authors investigate exergame design based on Gentile's motor skills taxonomy and describe the implementation details of the REWIRE games with an emphasis on patient motion tracking. More particularly, the use of Nintendo Wii in motor rehabilitation is reviewed and discussed in the next chapter. Chapters 18 and 19 focus on motor rehabilitation after stroke: the former reviews upper limb rehabilitation games whereas the latter describes a 3D visualisation system for biomechanical analysis of lower limb rehabilitation. Finally, Chap. 20 presents a maze game for training users at maintaining balance over various types of soil (broken stone, stone dust, sand, concrete and wood) with its physical setup and peripherals, including intelligent shoes, and reports the result of its initial evaluation.

Part five includes a serious of therapeutic games aimed at various diseases such as cystic fibrosis, Parkinson disease, and autism. Chapter 21 describes a system comprised of a Positive Expiratory Pressure (PEP) mask, a computer-connected pressure monitor and a suite of games of varying types, which encourage young sufferers of cystic fibrosis to participate in daily therapy. The authors also report finding based on game statistics and subjective feedback in order to determine long-term effects of this gaming therapy. Chapter 22 proposes a wearable Augmented Reality (AR) system for Parkinson disease rehabilitation. The users can perform different tasks in context–specific scenarios. By segmenting and overlaying users' hands and objects of interest above the 3D environment, patients have the ability to naturally interact with both real–life items as well as with augmented objects using their bare hands. The findings of a comparison study are report, where the tasks were carried out both in the real world and using the AR system in order to assess patients' performance. In Chap. 23, Garzotto, Valoriani and Bartoli explore the benefits of motion-based touchless interaction, where games are controlled using body movements and gestures without wearing additional devices, for autistic children with low-moderate cognitive deficit, low-medium sensory-motor dysfunction, and motor autonomy. They found that motion-based touchless gaming led to improvements of attention skills for the subjects.

Finally, part six consists of three chapters on virtual healing. In Chap. 24, Stone et al. provides a holistic discussion on the use of virtual restorative environments—the reconstruction of locations and scenes that, by virtue of their natural beauty and peacefulness, can significantly help to reduce the body's reactivity to stress and restore cognitive or attentional capacities, especially for amputees and patients recovering following surgical procedures. More specifically, Chap. 25 describes VR Graded Exposure Therapy (GEXP) as treatment for pain-related fear and disability in chronic low back pain. The final chapter looks at sound, a key aspect of VR, AR, and serious games that, because of the dominance of the visual sense, is often overlooked in the creation of healthcare applications. The authors discuss the importance of high-quality audio in rehabilitation applications and describe the equipment and processes of creating quality natural sound recordings.

1.3 Future Trends of VR, AR, and Games for Health

1.3.1 Location-Based Excergaming

Emerging and pervasive technologies bring lots of potential for location-based excergames (a.k.a. *ubiquitous gaming*), especially live action role playing games that take place both virtually in game worlds and in the real world, as people moving around in physical space to accomplish game-related missions that register in the game world, e.g. *Geocaching, Botfighter, Zombies Run,* and the recently launched *Ingress*. It is expected that location-based excergaming will develop over the next decade, particularly, on mobile platform, with wearable devices such as Google glass or smart watch. Readers who are interested in this trend should definitely read Chap. 11.

1.3.2 Mobile Apps

Although there are no healthcare apps for smart phones in this book, it is undoubted that mobile apps on mobile and tablets are changing the way providers and patients approach healthcare and the way of medical education, and that they will become more popular in the future. Some apps are designed for the healthcare providers, e.g. mobile app triage, handy databases about drugs and diseases, and monitoring patients' blood pressure, glucose levels or asthma symptoms; others are for patients, ranging from gathering diagnostic data to self-administration of medicine; and more for general public to promote active, healthy lifestyles.

1.3.3 Social Media Gaming for Public Health

Social media will have a growing role for health related games. Using social media to support exercising and brain fitness, to increase adherence to treatment, and to raise awareness of certain diseases is becoming more important due to the popularity of social gaming and the effectiveness of social interaction. This aspect of serious games is explored in Chap. 12. We believe that putting social psychology into health game would be another direction for future development of healthcare applications.

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Part I
Applications in Healthcare Education

Chapter 2
Healthcare Training Enhancement Through Virtual Reality and Serious Games

Sandrine de Ribaupierre, Bill Kapralos, Faizal Haji, Eleni Stroulia, Adam Dubrowski and Roy Eagleson

Abstract There has been an increase in the use of immersive 3D virtual environments and serious games, that is, video games that are used for educational purposes, and only recently serious games have been considered for healthcare training. For example, there are a number of commercial surgical simulators which offer great potential for the training of basic skills and techniques, if the tedium of repeated rehearsal can be overcome. It is generally recognized that more abstract problem-solving and knowledge level training needs to be incorporated into simulated scenarios. This chapter explores some examples of what has been developed in terms of teaching models and evaluative methodologies, then discusses the educational theories explaining why virtual simulations and serious games are an important teaching tool, and finally suggests how to assess their value within an educational context. The tasks being trained span several levels of abstraction, from kinematic and dynamic aspects to domain knowledge

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training. The evaluation of the trainee at each level of this hierarchy necessitates objective metrics. We will describe a unifying framework for evaluation of speed and accuracy of these multi-level tasks needed for validating their effectiveness before inclusion in medical training curricula. In addition, specific case studies will be presented and research results brought forward regarding the development of virtual simulations, including those for neurosurgical procedures, EMS training, and patient teaching modules.

2.1 Introduction: Games and Simulation in Medical Education

Learning health-related subjects during medical, nursing or any other allied health profession training involves the study of extensive material and the acquisition of a variety of new skills. Over the years, teachers have tried to incorporate new technologies as tools into the curriculum, to make the material more interesting and easier to learn. The ubiquity of videogame play today has seen a recent push towards serious games, that is, the application of videogame-based technologies to teaching and learning A study over 200 medical students in 2010 indicated that 98 % of medical trainees supported technology to enhance healthcare education and 95 % thought new media technology (i.e., game play) could be better integrated or used in the curriculum [1]. Leveraging this interest in new media by incorporating "serious games" into the surgical curricula may enhance surgical training for the current generation of learners [2]. Game-based learning "leverages the power of computer games to captivate and engage players/learners for a specific purpose such as to develop new knowledge or skills." [3] With respect to students, strong engagement has been associated with academic achievement [4].

The presence of this new media, however, is insufficient to ensure its effective use; the mode of delivery of educational content is also an important consideration. Although recent technology has made available an increasing number of surgical simulators, most are used infrequently by trainees. As a result, many surgical simulators sit unused in hospitals and simulation centres, except when they are specifically incorporated into structured educational sessions (e.g. weekend training courses) or used for demonstration.

A potential reason to explain the lack of use of these training tools beyond the confines of structured educational activities is that despite their potential educational value for training specific technical and cognitive skills, these simulators often lack specific design features that would make them enjoyable for learners [5]. Mastery of a skill requires repeated and deliberate practice. However, the instructional design of current simulators is largely focused on replicating the educational content using pre-defined activities that students have little control over; thus the process of practicing a skill on existing simulators until this mastery is achieved is not associated with the thrill inherent in games (e.g. winning a game or having the best score). As a result, motivation to engage in the deliberate practice necessary to glean the educational benefit from this technology is low [5]. In contrast to such traditional teacher-centered learning environments where the teacher controls the learning, serious games and virtual simulations allow the student to interactively control the learning thereby promoting an active, critical learning approach where the teacher now takes on the role of facilitator [6]. Although the term "serious games" is rather new, game-based learning has been employed for many years in a wide array of training applications, most notably by the military, and is currently growing in popularity in the medical education including surgery. This should come as no surprise, as the use of simulation in medical education has been widely accepted and according to Becker and Parker [7]. In the end, all serious games (or game simulations as Becker and Parker refer to them) are games, and all games are simulations and can employ identical technologies (hardware and software). Through game constructs, realistic situations can be simulated to provide valuable experiences that support discovery and exploration in a fun, engaging, and cost-effective manner.

Serious games have the potential of bridging the simulation and gaming worlds by harnessing the educational value of technology-enhanced simulation to teach specific technical or cognitive skills to learners (be they trainees or patients), alongside the motivational, interactive, and engaging aspects inherent in games. In addition to promoting learning via interaction, serious games are ideal for surgical simulation as that they allow users to experience situations that may be otherwise difficult to experience in reality, due to factors concerning cost, time, safety, and ethics [8].

One of the most expeditious ways to introduce new technology in the curriculum is to use it as part of serious games. The ubiquity of videogame play today has seen a recent push towards serious games, that is, the application of videogame-based technologies for teaching and learning. Serious games have been used in nursing curriculum since the late 1970s (1976–1977) first with role-playing, then using mannequins, finally progressively using avatars in digital games [9]. A complete discussion of serious games assessment is beyond the scope of this chapter; a more comprehensive review is provided by Bellotti et al. [10]. A short and non-exhaustive overview of published studies focusing on serious games to teach some aspects of health-care training is presented below. We searched several databases (Scopus, PubMed, Google Scholar) with the following keywords "serious games", "healthcare training" "medical students", "nursing", "games for education". Over the years, the technology associated with serious games and training has become broader, as well as their definition, and therefore the types of games developed vary from quizzes using cards to complex video games. In parallel to the games' design evolution, there has been some development in their evaluation with respect to training Fig. 2.1.

After serious games were introduced within nursing, the concept of game integration carried forward into other professional training scenarios [11, 12]. Role-playing, with someone taking on the role of a patient, interacting with the trainee, was one of the first types of serious games introduced in nursing education. For example, role-playing was used for training in mental health and psychiatry nursing, or in nursing for older patients [13–15]. However, to be considered as a game

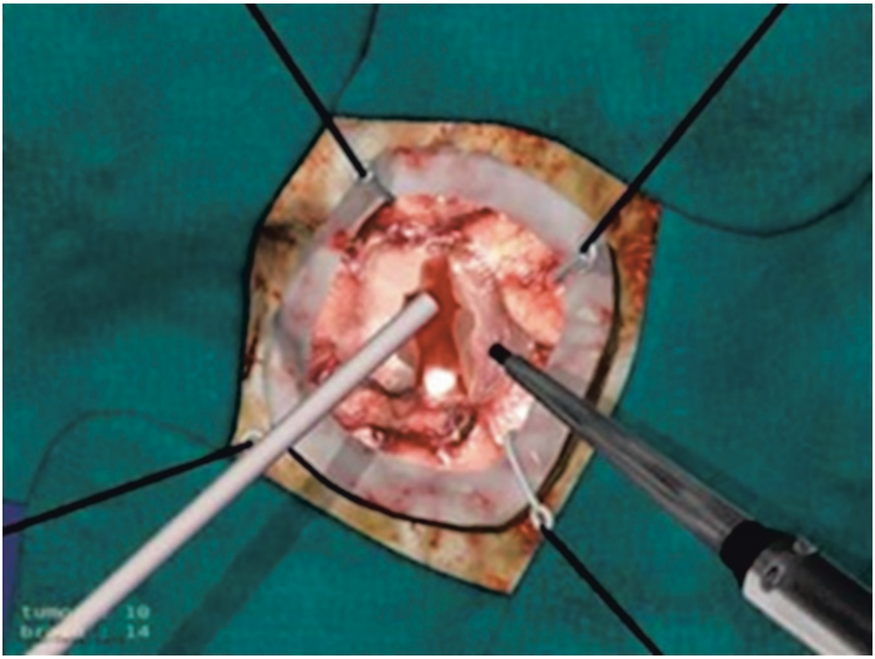

Fig. 2.1 Screenshot from the neurotouch designed by the National Research Centre Canada. The task of the trainee is to remove the whole tumour without removing the brain around it, and to minimize the blood loss

instead of just a role-playing experience, one has to introduce more structure or rules, and a better theoretical framework. Studies showed that there was an increased active participation and motivation when the skills where learned in a game environment [16]. Role-playing games where followed by scenarios gravitating around mannequins for cardio-pulmonary resuscitation [17], first only focusing on technical skills with low-fidelity mannequins, but increasingly more complex scenarios were developed, with higher fidelity mannequins (Fig. 2.2).

Game-developers attempted to implement quiz-based educational games using different strategies such as card picking and wheel turning, among others, in an attempt to make learning more attractive. Some researchers were also inspired by TV game shows. For example, “Pediatric Jeopardy” was based on the TV show Jeopardy [18]. Games have been applied to a variety of medical education topics. For example, games have been developed for medical trainees to learn about neonatal care [19], cardiovascular drugs [20], and abnormal blood clot formation [21]. Games have also been employed to educate medical students about basic principles such as physiology [22], microbiology [23], cancer genetics [24] and psychosocial aspects in paediatric [25] or geriatric calls [26], clinical practice guidelines [27], and even how to maintain a medical practice [28]. The same designs have also been used to teach specific treatments, such as starting an insulin treatment

Fig. 2.2 Example of an OR setting in a virtual reality world (second life) [96]

for diabetic patients [29], or the treatment of stroke [30], with learners showing a higher level of satisfaction with similar knowledge retention.

In general, studies examining appreciation of serious games and comparisons of serious games (quizzes, web-based or role playing) in nursing or medical students, have showed that students favour a serious game approach [1, 23, 24, 31–34], even if their scores were usually similar to "traditional" (non-serious games-based) teaching methods. At the resident level, junior residents were more interested and engaged within a serious game than the senior residents [35], indicating that serious games might have more effect early in the training rather than towards the end.

Despite the promise and potential of serious games to address many of the shortcomings associated with the current educational system, particularly with respect to addressing the learning needs of today's generation of learners, there is a lack of studies that have methodically assessed learning via games and this has prompted some to challenge the usefulness of game-based learning in general [4, 36, 37]. Further complicating matters are the results from a number of past studies that have reviewed the literature and conducted meta-analysis on "instructional games" focusing on empirical research on instructional effectiveness, which have questioned the effectiveness of game-based learning [38, 39]. Many of these reviews related to the effectiveness of simulations and games were conducted several years ago and the studies they focus on date back several decades. However, even in the last 10 years, there has been unprecedented development within the videogame field and it has been suggested that games more than five years old are "old news" [7]. That being said, there are also many examples of studies that have demonstrated that when designed properly, "learning games", do facilitate knowledge and skill acquisition (and plenty of it), while also engaging players [40–42].

Learning in general is a complex construct and difficult to measure. Thus, determining the effectiveness of a serious game (that is, determining whether the serious game is effective at achieving the intended learning goals) is a complex, time consuming, expensive, and difficult process [43, 44]. While most studies have shown more engagement of students and a higher satisfaction level among trainees when a game strategy is used to teach, a review in 2012 showed that in the 25 articles describing serious games for medical personnel training, none had a complete validation process [2]. Therefore more scientific and systematic ways of evaluating the satisfaction of the learners and the knowledge retained through this pedagogical approach needs to be incorporated into future studies, in order to have a more concrete view of how serious games can be implemented into the curriculum of health professionals. In addition, one should not forget that such games must accomplish specific learning goals that complement existing training methods. Debriefing must occur after the game, using the experience to point out meaningful events (especially errors made) and the correct approach that should be taken in future attempts.

It has also been shown that not all serious games result in improved learning [45, 46], which raises an important issue: without a good evaluation, one cannot be sure that 'negative learning' is not arising from the game. As stressed earlier, the content of the game as well as the objectives must be well thought of and recognized before and during the development of the game. It must then be tested on a pilot group, to of learners be sure that there are no misconceptions on the students' part since their understanding of the game and procedures to be done might not be the same as for the experts. This phenomenon has been well demonstrated in some medical simulator studies, as well as in other disciplines [47–49].

Example of serious game involving decision-making in surgery:

Total knee arthroplasty (TKA) is a commonly performed surgical procedure whereby knee joint surfaces are replaced with metal and polyethelene components that serve to function in the way that bone and cartilage previously had. Motivated by the fact that by clearly understanding the steps of the procedure and the underpinning surgical decision making processes, when placed in real operative environment, trainees will be able to focus on the technical aspect of the procedure, we recently developed a serious game for TKA procedure training (see [50]). The TKA serious game focuses on the cognitive aspects of the TKA procedure (i.e., the ordering of each of the steps in the procedure, and the various tools used at each of the steps). Users begin the serious game in the operating room taking on the role of the orthopaedic surgeon, viewing the scene in a first-person perspective (see Fig. 2.3a). Several other non-player characters (NPCs) also appear in the scene including the patient, assistants, and nurses (currently, the NPCs are not animated and are not user controllable but future versions will allow them to be controlled remotely by other users or controlled using artificial intelligence techniques). A cursor appears on the screen and the trainee can use this to point and interact with specific objects in the scene. "Selectable objects" include the NPCs (assistants and nurses) in addition to the surgical tools. When a highlighted object is clicked on, a menu appears providing a list of selectable options for this particular object. The surgical tools are also selected using the

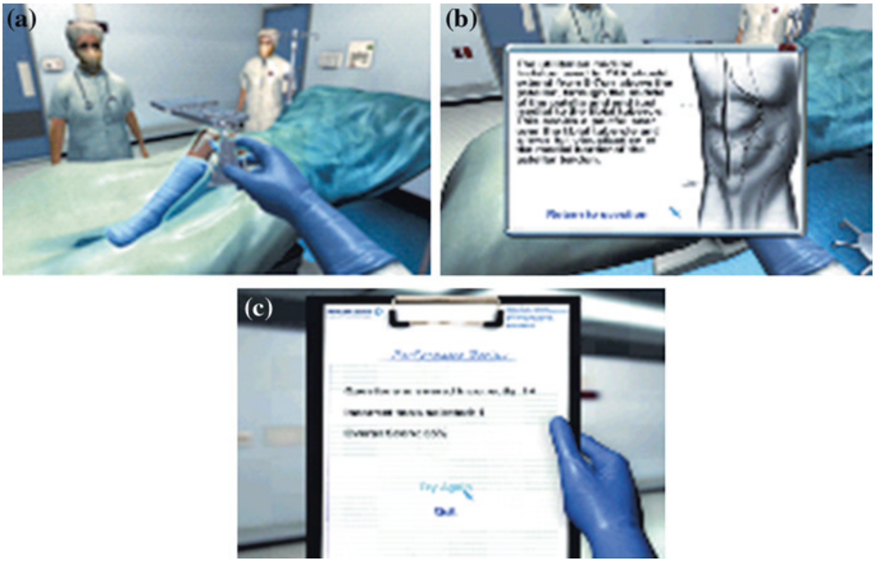

Fig. 2.3 Arthroplasty game: sample screenshots. **a** (*left*) The patient's leg glows to show that it can be interacted with. **b** (*right*) A pop-up window explaining why the user's answer was incorrect. **c** (*lower row*) The performance review screen shows the number of questions answered incorrectly and the number of times that the wrong tool was selected

cursor and once a particular tool is selected, the tool appears in the hands of the user's avatar. Once the tool has been chosen, if the patient's knee is selected using the cursor, a menu appears providing the user a list of options corresponding to that step. For instance, if the user chooses the scalpel and then clicks the patient's knee, a menu appears prompting the user to choose how big the incisions should be. Once the correct step is chosen, users are asked a multiple-choice question to test their knowledge of that step. Answering correctly results in a number of "points" earned, which are added to an accumulating score. If the user answers the multiple-choice question incorrectly, they are corrected in the form of text and/or illustrations (in a pop-up window) to ensure they understand why their answer was incorrect (see Fig. 2.3b). If they answer the question correctly, they are presented a short video segment illustrating a surgeon performing that particular step on a "real" patient with the surgeon narrating the details of the step). If the user chooses an incorrect tool for the corresponding step or performs a step out of order, they are corrected by a pop-up text-based monolog from an angry assistant surgeon. When the procedure is complete, the player is shown a score card listing the number of questions answered incorrectly, the number of tools selected out of order, and the overall score as a percentage of correct responses (see Fig. 2.3c).

A usability study conducted with both orthopaedic surgery residents and game developers revealed that the serious game was adequate with respect to allowing users to learn how to operate it, to learn advanced features, to explore and discover new features, and to remember previously used commands [50]. Moreover, participants believed that the serious game was properly designed to provide a logical sequence to complete tasks and that it provides feedback on the completion of particular steps. Recently, user-based experiments with orthopaedic surgery residents were conducted and results indicate that the game is effective with novice trainees.

Given the positive experimental results of the TKA serious game together with the positive feedback regarding the game in general, particularly from the medical/surgical community, we are in the process of applying serious games for the cognitive training of several other surgical procedures including the technically challenging and difficult off-pump coronary artery bypass surgical procedure [51], and the z-plasty, plastic surgery procedure training [52].

For example, Z-Doc was developed for training plastic surgery residents the steps comprising the Z-plasty surgical procedure. Z-DOC employs touch-based interactions and promotes competition amongst multiple players/users thus promote engagement and motivation [52]. Qin et al. [53] describe a serious game for the management of blood loss and replacement in orthopaedic surgery. Further examples include a serious games for total knee replacements education whose goal is to educate orthopaedic surgery residents about the steps of the procedure and the tools required for each step [50], a serious game for the off-pump coronary artery bypass (OPCAB) grafting cardiac surgical procedure [51], and finally, a serious game that was developed to examine needle placement under ultrasound guidance amongst radiology residents [54]. Serious games have also been used in CPR pre-training for medical students before a session using a simulator (mannequin) and have resulted in an improvement in CPR skills [55].

Moreover, we are also in the process of generalizing the application of serious games to cognitive surgical skills training through the development the serious game surgical cognitive education and training framework (SCETF) [56]. Domain-specific surgical modules can then be built on top of the existing framework, utilizing common simulation elements/assets and ultimately reducing development costs. The SCETF focus is on the cognitive components of a surgical procedure and more specifically, the proper identification of the sequence of steps comprising a procedure, the instruments and anatomical/physiological knowledge required for performing each step, and the ability to respond to unexpected events while carrying out the procedure. By clearly understanding the steps of a procedure and the surgical knowledge that goes along with each step, trainees are able to focus solely on the technical aspect of the procedure (i.e., the actual execution) in higher fidelity models or in the operating room thus making more efficient use of the limited available resources. Adequate cognitive skills can accelerate the understanding and planning of a particular procedure, and lead to a reduction in the training time required to become proficient with the procedure, thus creating more effective learning while making more efficient use of the limited training time in the operating room [57]. The SCETF is also being developed as a novel research tool, whereby simulation parameters (e.g., audio, visual, and haptic fidelity, stereoscopic 3D (S3D) viewing) can be easily adjusted, allowing for the systematic investigation of simulation fidelity, and multi-modal interactions with respect to learning. This will also allow us to build upon our current work that is examining perceptual-based rendering, whereby rendering parameters are adjusted based on the perceptual system to limit computational processing. Ultimately, this will lead to a better understanding on fidelity and multi-modal interactions on learning.

2.2 Does Video Game Proficiency Correlate with Surgical Skill?

Another focus of study over the last decade is whether video games have an effect on surgical skills or other health-related skills. Researchers have argued that playing video games may help in the eye-hand coordination, visual perception, visual memory, [58] and even fine motor control.

According to a recent review, 46 % of the studies examined showed an improvement in clinician skills outcomes and 42 % in health education outcomes—but the author identified that the study quality of those 38 articles as "generally poor" with few blinded researchers [59]. An example of those studies investigated whether good video game skills translate into surgical skills demonstrated that laparoscopic surgeons who played video games made fewer errors [60] or were faster in laparoscopic performance than their counterparts who did not play video games [61, 62]. The same results were replicated for endoscopic/gastroscopic surgery [63, 64] and robotic surgery. However, a number of studies have shown no difference in performance between video game players and their peers [65]. It is clear from this conflicting evidence that further research is required in this area.

2.3 Serious Games for Patient Education

In addition to training health care professionals, serious games can be used in different aspects of health care, such as to educate a patient, their family, and the general public about a disease or a medical/surgical procedure. There are different aspects of serious games for health that can be developed. The first category focuses on distracting the patient from their condition in an attempt to treat anxiety [66], nausea during chemotherapy [67], or pain during debridement of a burned wound [68] or other chronic painful treatment (www.breakawaygames.com/serious-games/solutions/healthcare/). The effectiveness of virtual reality and games used in the treatment of phobias and in distracting patients in the process of burn treatment or chemotherapy has been scientifically validated with the use of functional MRI (fMRI), which has shown differences in brain activity in patients who were experiencing pain with and without the use of virtual reality and games [69].

The second category (referred to as "exergaming") promotes physical activity through game play, using Wii, Kinect or even a joystick or special equipment (such as in GameWheels, which was developed for patient in wheelchairs) [70]. These games can be used to promote fitness or rehabilitation and have been used in traumatic brain injury [71–73], stroke [74], or limb deficit after trauma or stroke [75, 76].

The third category involves teaching the patient or the patient's family about the patient's condition and how to manage it more effectively. For example, in a game designed to teach children about asthma, Bronkie the Bronchiasaurus needs to avoid triggers, or the child creates an avatar of a secret agent spying about asthma management [61]. As a further example, consider the games designed for diabetes, where the user is provided with tricks regarding the management of insulin and general nutrition, in order to influence patients' dietary choices [77]. Case scenarios, and other games have been developed to explain surgical procedures to patients. For example, there is an interactive tool to describe deep brain stimulation surgery, or an aneurysm repair to children in a classroom, which could be used for patients [6, 53].

2.4 Games and Play: Structured Learning Versus Entertainment

The mechanisms underlying the educational benefits of serious games lie in their capacity to improve the enjoyment, engagement, and motivation of learners as they engage with educational content that they are required to learn. "Serious Games" are generally proposed as a potential solution to the fact that receiving education formally is often seen as requiring hard work, and work is not necessarily enjoyable. The typical distinction made between activities that are 'work' and 'play' hinges on the motivational aspects behind these activities: play is done spontaneously or by choice and work is typically imposed, prescribed, or done for remuneration.

There are important definitive characteristics of all games: they are activities in which a player works, through interaction with an environment, towards a goal. In the process, a player conquers challenges in an attempt to achieve the specified goal, without any certainty that it will be attained. If more than one player attempts the goal independently in order to show better performance than others, then it is a competition. If players interact within the framework of the game in a way that can interfere or interact with the other's performance, then it is a multiplayer game.

In common use, the word "game" refers to an activity that has no consequence in the real world. Despite this, consider "Game Theory": the study of rational decision making under conflict or cooperation. Interestingly enough, game theory is conceived to model and explain the interactions of agents in the real world. Game play can be enjoyable, and, at the same time, allow the player to practice a set

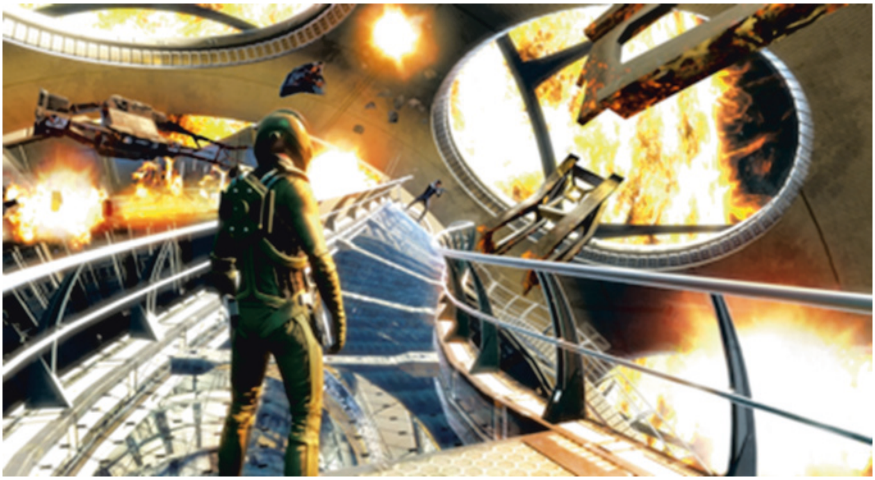

Fig. 2.4 Example of an engaging game with realistic images (image courtesy of digital extremes, Inc)

of skills; in a relatively constrained and risk-free version of reality. In this sense, 'game play' can have a bearing on the real world, as the player can improve skills that can lead to better performance on related tasks in the real world—a concept known as transfer [69, 78]. Certain aspects of gaming and playing should be examined with regards to learning:

- Games are goal-driven activities
- Games involve interaction between the player(s) and a represented world
- Game interactions are constrained or governed by rules
- During a game, progress towards the goal can be evaluated, even though there is no certainty that the goal will be attained
- Games are adaptive to the level of the player
- Games and play are enjoyable and engaging
- Play, when appropriately designed, results in the learner developing a skill or knowledge that can be applied to the real world.

There is a fanciful sense in which games might be proposed as an ideal mode for teaching. Squire and Jenkins (2003) note that in the science-fiction novel, Ender's Game [79], in which the earth is threatened by an alien invasion, the response is to raise a group of specially selected children,

"…trained through a curriculum that consists almost entirely of games—both electronic and physical. Teachers play almost no overt role in the process, shaping the children's development primarily through the recruitment of players, the design of game rules, and the construction of contested spaces" [80] Fig. 2.4.

In this way, open game play serves as the substrate for curriculum delivery, in accordance with current constructivist theories of learning, where the learner is in the "driver's seat" and the traditional role of the teacher or the instructor is replaced by that of a facilitator. Psychological constructivist learning theory argues that learners actively construct meaning of phenomena through interactions with their environment, in a process where what they already know contacts ideas and knowledge that they are exposed to [81]. "Card's school is a constructivist utopia—in that nobody teaches kids what to do in these games; they are left on their own to experiment and solve compelling problems" … "And the games automatically adjust to the skill level and objectives of each student" [80].

The concept of 'unconstrained play' also brings into sharp focus the necessity of a clearly articulated curriculum and well-designed instructional content for these games. This raises a number of important questions, including: If a set of games allow for engaged yet risk-free training, then who selects the games? Who ensures that they are sequenced in a useful order for the learner? How are the games adapted to the current level of the learner to ensure the optimal degree of challenge without cognitive overload [82, 83]? And if the games are so engaging, then who stops the gameplay to ensure that the trainee does not over-learn one small fragment of a necessarily broad skillset? In other words, who plays the role of instructional designer and facilitator?

Constructivism has always emphasized the role of the teacher as a guide, and the importance of the staging of the curriculum [84–87]. This is clear when we examine Piaget's levels of development [88]. First, individuals need to learn at a sensorimotor level, followed by a more abstract level in which symbolic information may be acquired through learning about objects and their properties, or through verbal instruction. The third stage is 'operational' in the sense that external rules and behaviours can be used within a framework of logical reasoning. Finally, the formal operational stage corresponds to a level of expertise in which alternative plans and hypotheses can be formulated and evaluated, and combined with general abstract knowledge [89]. Although these stages are regarded typically as being applied to general learning from infancy, Piaget's incremental learning process fits equally well to the abstract levels of complex task analysis [90], as applied to a set of levels of abstraction in complex task learning [91] for surgical training or within a broader healthcare context.

Constructivist theories emphasize the necessity of staging learning in a way that spans these levels, and recognize that one level of learning is predicated on scaffolding upon other levels. The notion of 'scaffolding' educational experiences is seen among many social constructivist curriculum designs that are applicable to serious games, including the spiral curriculum model [77] and Lev Vygotsky's model of training within the "Zone of Proximal Development" of a learner [92]. Thus, to the extent that 'games' may be appropriate forms of activity for learning, the set of games needed to teach complex clinical and surgical skills, and the order in which they are presented to a learner, need to reflect these levels [93]. What remains, therefore, is to examine how the set of games can be mapped onto the set of sub-tasks, which comprise an overall complex task from its hierarchical task decomposition.

2.5 Hierarchical Task Analysis for Game Scenario Design

To introduce the notion of Hierarchical Task Analysis within a clinical setting, let us consider the phases of any clinical or emergency situation: situational assessment, decision making, task selection and sequencing, followed by the task activities. For example, in an emergency medical response situation, first responders arriving on a scene begin with a situational assessment. This is followed by some cognitive, problem-solving processes, towards a decision making to stabilize the situation. Finally, based on their decisions, the responders will take action performing a variety of tasks or direct actions.

The characteristic of all tasks that are accomplished in a real or virtual world is that they are comprised by low-level sensori-motor actions. Examining the surgical task in detail, we recognize a kinematic level (kinematics of reaching, grasping, cutting, and piercing) and a dynamic level (control of forces needed for pulling, cutting, piercing, and probing). This descriptive account can be defined in terms of a Surgical Skills abstraction hierarchy [91], including:

- ‘Knowledge Level’ or Cognition (assessment)
- Decision-theoretic (reasoning, planning)
- Sequenced ‘Action Scripts’ or tasks (rehearsed responses to typical scenarios)
- Sensori-motor Kinematic Skill (targeting, positioning, grasping, moving)
- Sensori-motor Dynamical Skills (forces, balance, pressure).

Using these levels, we propose to decompose the concept of a ‘training scenario’ into layers of abstraction [91]. This hierarchy is similar to those posed by Albus [90] to describe the abstract levels of control that need to be considered when controlling a complex mission using telerobotic control of a remote robot.

At the lowest levels, the training aspect is at the skill level, where movements and actions involving hand-eye coordination are converted to visual-motor programs. The skills are evaluated by measuring the speed/accuracy of the movements (Fitts’ paradigm [94]). As we move upwards through the hierarchy of levels, training involves skills that are composites of skills at the lower level. In effect, tasks, like suturing, are skills that are comprised by low-level movements: grasping and pulling, and are repeated and controlled with a set of rules, which initialize, iterate, and complete the movement. In composite actions, the notion of ‘task time’ and ‘accuracy’ can be specified in terms of the individual task times of the composite movements, or as the overall sum. Similarly, for accuracy, the objective score for, a row of sutures as an example, can be based on an assessment of the individual positions of the run of stitches, or by an overall measure of the uniformity of the pattern [95]. Pursuing this argument further, as we move upwards through the hierarchy, the skills being trained are posed in a vocabulary that may include tasks like opening or closing (which in themselves comprise sub-tasks). In opening, the surgeon will cut the skin, achieve hemostasis, and reach their target; while for closing: the surgeon will finalize the hemostasis, close the incisions with sutures and apply a dressing.

We assume that objective measures of the skill level of the trainee will be posed in terms of some speed and accuracy measures—yet these become overall scores typically. In surgical assessment, these are often reported as 'outcome measures', and can be a mixture of subjective and objective scores. However, whether training is performed using serious games or VR simulators, these outcome measures can be determined objectively if the training software is designed to measure the movements and response times of the trainee. If the evaluation can only be posed in terms of 'speed and accuracy' at any one of the levels of abstraction, the scores for evaluating the effectiveness of training at any particular level of the task hierarchy can be composed by aggregating the objective measures of the subtasks at a lower level of abstractions.

2.6 Knowledge Level, Procedural Levels, and Basic Skills Level

Let us now discuss the levels of knowledge and skills involved in the surgical process, how they relate to each other and how they may be assessed.

Domain Knowledge At this level, we include the knowledge and skills relevant for diagnosis, namely the logical reasoning necessary for evaluation of the situation and the patient. One must assess the patient, bringing to bear all of their relevant medical knowledge, applying it specifically to that situation, while integrating the patient's history and the various laboratory and imaging results. It is therefore an integration of current information on a patient with previous knowledge in order to obtain a differential diagnosis. One will confront different working scenarios and hypotheses arising from the patient's condition to previous knowledge to try to construct this diagnosis.

Planning and Decision Making Here, we incorporate the decision processes arising during the care of a patient. For example, when a patient arrives in the emergency room, the triage nurses have to decide whether the patient needs to be lying down and has to be seen immediately or whether some wait time is acceptable. While the full diagnosis is not needed, some key words will trigger different responses. One can plan to lay the patient on a stretcher, to start an intravenous fluid infusion, to call the emergency physician. The decision making involves grouping, coordinating and communicating a number of tasks among several individuals and diverse disciplines to achieve a result. Evaluation at this level may include considerations of time and agreement of the enacted plan with those of experts.

Task-level activities occur within a small time frame involving a motor action and may also require a basic decision. At this level, we include activities such as starting an intravenous infusion (one looks for a good vein, prepare the skin with an antiseptic solution, open the iv packet, then pierce the skin with the needle, advance it in the vein, etc.). Tasks may be simple with no decisions involved (such as tying a knot) or composed of sub-tasks (for closure, the surgeon or trainee must decide how far apart to make the stitches, or what type of suture (single, continuous running etc.)). Tasks can be difficult to assess, since there may be no explicitly "true or wrong" task executions, so timing can still be examined (especially in simple tasks), but accuracy is more important than error rate (not binary but scaled).

At the movement level (kinematics), we examine aspects such as the displacement in space with surgical instruments to reach a target, the movement needed to cut a tissue or to grab an organ to displace it. For example in endoscopic surgery, the surgeon has to reach the target with the forceps while looking at the screen. At this level, assessment involves calculation of the speed and accuracy of the movement.

Finally, at the *dynamics level* (forces, etc.) we examine physiological control, such as the force with which a surgical instrument is grasped. One can look at the amount of pressure exerted on scissors to cut a tissue, the force with which a needle driver is handled, the pressure exerted on the forceps handles and therefore to the forceps tip in order to use them. Repeated use of tools and training might change the handling of instrument, and therefore experience and decreased stress level during a procedure might also explain the differences between novice and expert.

Therefore when analyzing a scenario, one has to take into account the layers mentioned above in order to decompose the task hierarchically. Objective measures based on speed and accuracy at all levels of the abstraction hierarchy provide for an evaluation mechanism of the learning process, and also serve as the 'scores' for this serious gaming activity.

2.7 Conclusions

When considering the definitions and differences between the terms "game", "play", "work", and "task", it becomes clear that games and tasks are almost synonymous, except for the notion that one is typically perceived as enjoyable and the other as tedious. The fact that games are scored and quantifiable (just as task performance), is what makes them well suited within an educational context. The scoring in a game gives immediate feedback to the users, but usually only reflects a small portion of their performances. While it is useful to keep the trainee engaged, and helps them strive to achieve a better score, the scoring systems currently developed are usually not giving enough information on what was done correctly and incorrectly to help the user improve as efficiently as with a formative feedback.

To make a successful serious game, one must first evaluate the needs of the envisioned learners, and decide what are the skills or knowledge than one want to teach. The learner's profile will be part of the constraints. Domain experts as well as educators will have to be part of the development and work in collaboration with the computer software or game developers. In addition to its domain-specific content, the game must be fun and challenging, with some type of story adapted to the trainee. The interactive nature of the game will help the user become immersed in the game. The age of the subject that one wants to train is also important, to decide on how long one can maintain the subject's attention, whether we want to make it in a fantasist or realistic world, since the motivation to play the game will vary with age. Last but not least, after the game has been designed, it needs to be evaluated to study the retention (short and long term) of knowledge/skill acquired by the subject playing the game. Objective measures based on speed and accuracy at all levels of the abstraction hierarchy not only provide an evaluation of the learning process, but serve as the 'scores' for these serious gaming activities for healthcare education.

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Chapter 3
A Haptic-Based Virtual Reality Head and Neck Model for Dental Education

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Abstract There have been numerous datasets, 3D models and simulations developed over the years however it is clear that there is a need to provide an anatomically accurate, flexible, user driven virtual training environment that can potentially offer significant advantages over traditional teaching methods, techniques and practices. The ability to virtually train dental trainees to navigate and interact in a repeatable format, before directly engaging with the patients can measurably reduce error rates while significantly enhancing the learner experience. Accurate dental simulation with force feedback allows dental students to familiarize with clinical procedures and master practical skills with realistic tactual sensation. In this chapter, we review the state of art of using haptics in dental training and present the development and construction of a medically validated high-definition interactive 3D head and neck anatomical dataset with a haptic interface to support and enhance dental teaching across multiple training sites for NHS Education Scotland. Data acquisition from cadaveric specimens and 3D laser scanning of precision dissection is discussed, including techniques employed to build digital models capable of real-time interaction and display. Digital anatomical model construction is briefly described, including the necessity to clinically validate each stage of development that would ensure a normalised human data set whilst removing anatomical variance arising from individual donor cadaveric material. This complex digital model was transformed into a real-time environment capable of large-scale 3D stereo display in medical teaching labs across Scotland, whilst also offering the support for single users with laptops and PC. The 3D viewer environment also

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supports haptic interaction through a force feedback probe device (Phantom Omni) offering the ability for users to repeatedly practise giving dental anaesthesia injections into the gum. Specific tools supported include guillotine tools, picking and selection tools capable of expanding specific local regions of anatomy. Zoom camera functions and freeform rotation allows thorough and meaningful investigation to take place of all major and minor anatomical structures and systems whilst providing the user with the means to record sessions and individual scenes for learning and training purposes.

3.1 Introduction

As it is already routinely applied to many scientific fields, 3D scanning technology, including laser scanning and white light scanning, are now being used to explore applications in medicine. In healthcare, the technology has also been used in development of prostheses [1]. Translated scan data can be immediately usable in computer aided design software, improving the speed of development of prosthesis. One of the limitations of laser scanning technology is that it is only able to capture and reconstruct the outer surface of the body, therefore the scans do not have any internal structure and physical properties regarding skeleton, skin or soft tissues of the scanned human body, unless it is combined with cadaveric dissection [2].

On the other hand, medical visualization based on direct and indirect volumetric visualization uses data derived from 3D imaging modalities such as Computed Tomography (CT), Magnetic Resonance Imaging (MRI), cryosection images, or confocal microscopy [3]. Although, the visualization is generally accurate, it only represents a particular human body or cadaveric specimen. Demonstrating a normalised anatomically correct model is difficult due to the source of data, the largely elderly population of cadaveric specimens. In indirect volume visualization where individual surface models are reconstructed, mistakes and inaccuracy might be introduced from the manual or automatic segmentation process; whereas in direct volumetric visualization, interactivity is limited since surface geometries are not reconstructed [3]. As a result, the users are not able to manipulate the model (volumetric data) as they could on surface models. Functions such as virtual dissection, e.g. disassemble/reassemble, and studying individual substructures are not possible. Furthermore, each imaging modality has its limitations, for example, for cryosections, the cadaver had to be segmented into large blocks which results in a loss of data at certain intervals; for CT/MRI images, segmentation rarely focuses on very thin anatomic structures [4] such as fascia. Developing a model that can present thin anatomic structures would be of great interest to medical professionals and trainees. However, the ability to accurately segment very thin structures is a challenging and substantial task.

In this chapter we present an established workflow using state-of-the-art laser scanning technology and software for design and construction of 3D medical data, and describe the workflow practices and protocols in the Head and Neck Anatomy

Fig. 3.1 The head and neck system was presented in the large scale virtual reality laboratory

project at the Digital Design Studio (DDS). The workflow overcomes the above limitations in volumetric visualization and surface anatomy.

This work was conducted by a well-established, unique, multi-disciplinary team drawn from art, technology and science. The team includes computer scientists, 3D modelers, mathematicians, artists and product designers, and supports a culture of research and creativity which is fast moving, highly productive, externally engaged and autonomous. This successful academic hybrid model is built upon strong collaborative partnerships directly with industry and end users, resulting in tangible real-world outputs. We have sought to establish a balanced portfolio of research, teaching and commercialization operating within a state-of-the-art, custom built facilities located within the heart of the Digital Media Quarter in Glasgow. For instance, the DDS houses one of the largest virtual reality and motion capture laboratories in the world ensuring that we are at the forefront of digital innovation, developing products focused on immersive virtual environments, highly realistic digital 3D models and prototypes, user interfaces and avatars. The virtual reality laboratory enables 30–40 users to simultaneously experience real-time and interactive simulations as shown in Fig. 3.1.

This haptic-based 3D models of head and neck anatomy has been used to educate health professionals and to support activities such as pre-operative procedure planning and surgical simulation in order to improve risk management and thus increase patient safety. This work has recently received significant recognition in the RCUK report *Big Ideas for the Future* [5].

3.2 Haptics in Dental Training

In dental education, specific training needs to be conducted to allow dentist apprentices and dental hygienists to acquire the psychomotor skills that are required to achieve complex clinical procedures such as anaesthetic injection, oral and maxillofacial restorative surgery, and dental implant preparation [6]. Traditionally, that training occurs under the supervision of dental experts and is carried out on plastic replicas of human jaws or live patients [6–9,]. However, that training is limited to the availability of experts for supervision [10] and its effectiveness is mainly established on the basis of a subjective assessment of performance outcomes [11, 12]. Moreover, training on replica model is often considered to not to be challenging enough [6, 10] and lacks of tactile realism of human tissues [9, 12]. On the other hand, training on live patients has been shown to be a source of anxiety for novice dental students [13, 14] and may eventually be critical from an ethical perspective [8].

Virtual Reality (VR) simulations allow solving those issues that arise throughout the training conventionally carried out in dental education [6, 8–11]. An important concept of VR simulations to support the development of psychomotor skill in dental education is the haptic interaction [15]. Effectively, graphic and haptic cues are considered to complement each other throughout VR simulations [7].

The term *haptic* refers to the *sense of touch*. Haptic interfaces enable providing realistic tactile and kinesthetic feedback allowing the simulation of tactile sensations that are crucial throughout dental procedures [16], for instance the stiffness and friction properties of human tissues [6, 9, 11, 15].

During these last years, dedicated research efforts have been made to develop challenging applications of VR enhanced with haptics to improve the acquisition of psychomotor skills during training in dental education [6, 8, 17]. Some of those applications have been validated and are nowadays part of the dental curriculum of colleges of dentistry across the USA and the EU [6, 8, 18].

This section proposes an overview of most successful applications that have been developed recently. Most of these developments propose cost effective solutions for the implementation of haptic interaction in virtual environments employing punctual inter-actuator such as computer gaming haptic devices from Novint Technologies (http://www.novint.com/) [12] or low cost interfaces from the Phantom product of Sensable Technologies Inc. (http://www.geomagic.com/en/) [6, 8, 18]. Most of these devices, in the proposed setup, are able to sense hand's position and orientation onto 6 Degrees Of Freedom (DOF), but can only provide force feedback onto 3DOF. In most developments, this has been highlighted as a limitation to the fidelity of the simulated tactile sensations. Moreover, the haptic rendering did not consider multi-point collision detection and single point-based collision was performed with regards to volumetric data set which often implicated a high computational cost [6] when no optimization was implemented (e.g. BSP Tree, octree data structure).

The HAP-DENT system [19], was presented as a promising educational tool for dental procedures [20]. It enabled practicing tooth drilling operations on a virtual jaw model displayed on a bi-dimensional monitor. The system was heuristically parameterized allowing defining a realistic force feedback model using a custom-made force measurement system. So far, no validation study on dental apprentices has been conducted to assess the effectiveness of the system to support psychomotor skill acquisition.

An original development of oral surgery simulator, known as the Forsslund system, was presented in [21]. It consisted of a *working prototype* to practice teeth drilling using a haptic device which computed volumetric tooth data and a semi-transparent planar mirror setup on which an active stereoscopic monitor was reflected allowing thus to visually match the haptic workspace with that of the virtual environment. The effectiveness of the suggested training tool to improve dental education has been highlighted in an evaluation study [22]. This system has been recently incorporated to the training curriculum of the Academic Centre for Dentistry Amsterdam (ACTA), Netherlands [8].

The PerioSim© [16, 23] was a highly realistic training platform which aimed to improve skills on diagnosis and treatment of periodontal diseases. It included the stereoscopic visualization of a jaw data model and supports haptic interaction. The haptic device enabled the manipulation of the probes that are necessary for the realization of periodontal tasks. A previous evaluation study has highlighted the potential of the PerioSim© for educational purpose [7]. It is currently employed as part of the dental training curriculum of the University of Illinois in Chicago.

The HapTEL [12] consists of a training and assessment platform which supports physical practices of caries removal for which drilling operations are commonly carried out. As in [21], it presented a setup in which the haptic and visual workspaces were visually matching. However, the trainee's point of view was tracked so that visuo-haptic matching remains more accurate than that proposed in [21]. The originality of that development was that the haptic device did not model the training instrument but the deformation of the drilled tooth tissues. In fact, the trainee handled a real drilling instrument attached to the sensed tip of the haptic device.

Initially thought for bone drilling simulations [24], the Voxel-Man Dental simulators supported training on drilling operations commonly performed previously to dental restorative treatments. Alike the developments presented above, it allowed to stereoscopically display a virtual mouth model but also enabled bi-manual haptic interaction. A virtual drilling tool was handled in one hand and another instrument in the other (http://www.voxel-man.com/simulator/dental/). The concept of Voxel-Man simulators have been through a complete validation process enabling to be currently a successfully distributed training platform which allows generating subtle and convincing tactile differences between tissues [18].

Similarly, Suebnukarn et al. [25] proposed a haptic-based VR crown preparation simulator on isolated teeth enhanced with bi-manual haptic interaction. The proposed system enables assessing psychomotor skills in real-time and providing augmented feedback to support the successful development of the psychomotor skills required in such restorative operations [26]. An advanced version of the development proposed the implementation of the training principles in an Augmented Reality (AR) environment enhanced with similar haptic paradigm [27].

The Simodont Dental trainer [28] by Moog Inc. (http://www.moog.com/) consists of an educational tool to support training of drilling operations. Evaluation has demonstrated that Simodont Dental trainer has similar effectiveness to improve psychomotor skills than the training traditionally carried out on anatomical mock-up. As the development presented in [12, 21], the system used a mirror setup to support the stereoscopic visualization of volumetric teeth data but used an admittance haptic device that similarly, provided force feedback onto 3 DOF. Alike the Forsslund System [21], the Simodont Dental trainer has been also incorporated to the training curriculum of ACTA [8].

The VirDentT [8, 29] is prosthodontal training and assessment tool enhanced with haptic interaction. Alike the Voxel-Man Dental, It allows practicing restorative dental preparation tasks for fixed dental prostheses. It simulated a virtual drill along with a patient jaw. However, little information is available concerning technical details of the system and more investigation is needed before formally considering it as an effective training platform.

A haptic-based dental simulator, the iDental [30], consists of a training system at an early stage of development and evaluation. It currently supports the learning of psychomotor skills involved in periodontal procedures but aims to be extended to endodontal and prosthodontal operations. Training is carried out on a virtual mouth model in which symptoms of periodontal inflammations are shown. A haptic device is used to handle virtual probes needed to complete the treatment. The evaluation study presented in Wang et al. [30] suggested the construct validity of the system although the fidelity of graphical and haptic cues still needs to be improved.

Despite the many research efforts realized in order to improve training curriculum in dental education, it has not been reported so far, haptic-enhanced VR simulations to support training in pre-clinical procedures such as the inferior alveolar and lingual nerve block anaesthesia injection technique. Closest approaches considered an anatomical jaw model made of latex, which attempted emulating intrinsic haptic sensations perceived during the realization of the task in the real world, while practicing in an immersive virtual environment [31]. With regards to VR simulations of epidural injections, catheter insertion, needle biopsy lumbar puncture and virtual acupuncture presented during these last years in order to improve medical training [32, 33], VR enhanced with haptics is expected to play a growing role in the training curriculum of pre-clinical pinching procedures in dental education [34, 35].

3.3 Development of Head and Neck Anatomy

NHS Education Scotland (NES) launched a European tender to develop a four strand work package to develop digital content for interactive Head and Neck anatomy, instrument decontamination, virtual patients and common disease processes for dentistry. This was a complex project requiring high levels of interaction across multidisciplinary development partners, in order to build a digital anatomy model (the 3D Definitive Head and Neck) and other digital products for medical teaching, across a distributed network of centres and primary care settings. The research took place within established protocols concerned with government legislation and patient interaction where the security of data and appropriate interface development were key factors.

This chapter discusses and focuses on the Work Package A, i.e. the 3D interactive Head and Neck Anatomy. The aim of this project, commissioned by NES, was to complete the construction of the world's most accurate and detailed anatomical digital model of the head and neck using state-of-the-art data acquisition techniques combined with advanced, real-time 3D modelling skills and interactive visualization expertise. It was felt essential that this digital model must be capable of real-time interaction supporting both medical training and personal exploration, with all 3D data models and information being fully annotated, medically validated, and interactively "disassembled" to isolate and study individual substructures then reassembled at the touch of a button. In order to create a truly accurate interactive digital 3D model of head and neck anatomy it was essential to base the models upon real data acquired from both cadaveric and live human subjects. The full range of digital products was formally launched in April 2013. User feedback from NES medical teaching centres and primary care settings has been extremely positive.

This model integrates different tissue types, vasculature, and numerous substructures that are suitable for both the casual user and, in particular, those engaged in medical learning and teaching. Our model and software interface provides fluid and intuitive ways to visualise and encourage meaningful engagement with human anatomy amongst diverse audiences and is currently being well received by medical trainees, clinicians and the general public. Our 3D digital model development process, including data acquisition, model construction, interface design and implementation has been critically evaluated and validated by multi-disciplinary experts in the fields of medicine and computing science. Our extensive collaborative research network includes senior clinicians, surgical consultants, anatomists and biomedical scientists within the NHS, formal links with the medical schools within the Universities of Glasgow, Edinburgh, Dundee, Manchester and London, and other key specialists in the Scottish Medical Visualization Network.

Our systematic review of the medical visualization landscape indicated that there was an unmet need for validated anatomical visualizations of the healthy human body that could be relied upon by viewers as accurate and realistic reproductions of the *real thing*. Indeed, within medical, dental and surgical curricula, the number of actual contact hours for teaching has markedly reduced over recent years. Within the medical curriculum alone, the General Medical Council issued guidelines to medical schools in the United Kingdom (*Tomorrow's Doctors*, 1993) requesting a reduction in the amount of factual information [36]. This has happened across many medical schools across the world [36–38]. However, medical training programs also began to change to a more integrated curriculum with various teaching methodologies adopted. More recently in the UK, Tomorrow's Doctors 2009 has placed more emphasis on the medical sciences related to clinical practice. This directly reflects opinion from academics, clinicians and students that the anatomy content had been significantly "dumbed down" previously [39].

Thankfully, this is changing within medical, dental and surgical curricula. Interestingly, with these changes, it has also been shown that to optimise learning,

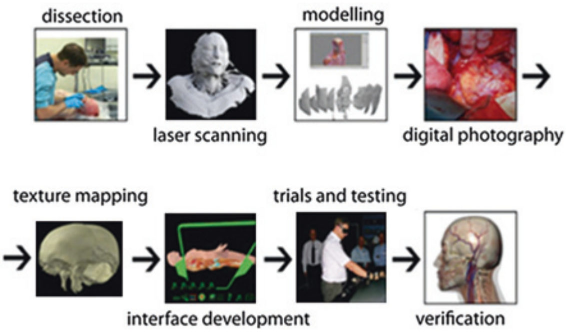

Fig. 3.2 Development workflow

a variety of teaching modalities need to be used alongside traditional techniques. There is now an increased demand from anatomical educators for additional teaching resources, including those of a virtual nature and involving interactive multimedia [40–42]. In addition, the general public has no means to view and interact with a truly representative visual simulation of the human body in a way that provides a genuine educational experience to promote public understanding of health and wellbeing. Using visualization experience gained within the automotive, defense and built environment sectors alongside medical visualization research, we sought to address these shortfalls by constructing a high fidelity 3D dataset, supporting *meaningful* user engagement, viewing and real-time interaction.

The primary focus of the virtual head and neck anatomy is on user interaction with real-time digital data that supports multi-disciplinary skill sets. It is built upon through 3D laser scanning, 2D data capture, data processing and optimisation, 3D construction of objects and environments, photo-realistic rendering, user interface design, real-time display and cross-platform development.

Figure 3.2 shows the development workflow, which at a high level, consists of identification of a suitable donated cadaver, dissection, 3D laser scanning capturing surface measured data, 3D computer modelling of all structures, digital photography from surgical procedures, texture mapping (colour information onto 3D surfaces) and interface development to support user interactions, trials and testing. Verification and validation is conducted at every development stage with final results being presented to a clinical advisory panel who met every three months throughout the project period.

3.3.1 Data Construction

An important consideration with a project of this size is the sustainability of the workflow, tools and datasets that are generated over its duration. One of the dangers of working within the computing industry is that software and proprietary data formats can often become obsolete over time resulting in data that cannot be read or used. Consequently, it is good practice to ensure that any valuable data is stored using standardized, open and well-documented formats to ensure that it is not reliant on a single company or piece of software to be used. We adopted such an approach for the storage and preservation of the head and neck anatomical datasets. The data generated throughout this project can be separated into two groups. The first group encompasses the raw data such as photographic evidence and point cloud data generated from white light and 3D laser scanners. The second group includes the processed data created by the DDS modelling team. The non-specialist nature of the raw data enables us to store it using open file formats such as the Portable Network Graphics (PNG) format for photographs and images and the Stanford Triangle Format (PLY) for scan data. However, in order to process this data and create anatomical models, more specialist proprietary tools and data formats are required. Since this cannot be avoided, we used industry standard tools such as Autodesk's Maya and Pixologic's ZBrush to generate and store these models. In order to ensure long-term sustainability, the textured meshes are also exported and stored using an open format such as COLLADA to insure against any of these products becoming obsolete in the future.

3.3.2 Data Acquisition

We have developed a completely new approach to medical visualization. Our novel data construction workflow and validation process uses donor cadaveric material and through the process of destructive dissection and staged, high resolution laser scanning allows us to produce an accurate 3D anatomical model of head and neck anatomy. To ensure accuracy and a true likeness of the human body, this dataset was validated by the project's Clinical Advisory Board, which comprises anatomists, clinicians and surgical specialists. Our dataset and interface development focuses on real-time interactive simulation (not pre-rendered animations) which allows users to fully explore the complete anatomical structure and investigate in 3D at any scale, from a laptop or mobile device to a fully immersive environment (see Fig. 3.1).

3.3.2.1 Selection of Specimen

The identification of a suitable embalmed male Caucasian cadaver between the ages of 50–65 was the starting point for this work package. This was identified from the regular stock in the Laboratory of Human Anatomy, School of Life Sciences, College of Medical, Veterinary and Life Sciences at the University of Glasgow. The cadaver had no obvious signs of pre-existing craniofacial abnormalities. All procedures were carried out under the Anatomy Act 1984 and the Human Tissue (Scotland) Act 2006. This was undertaken by the government's Licensed Teacher of Anatomy. This formed the basis of the definitive 3D digital human, with the head and neck region comprising the element to be described. Minimal pre-existing age-related changes were present, significant because the majority of cadavers are of those who have died in old age, many of whom are edentulous. The alveolar bone and teeth were recreated digitally based on laser scans of disarticulated teeth, held at Glasgow Dental School.

3.3.2.2 Dissection and Data Capture of Head and Neck Soft Tissue

The high resolution 3D laser scanning supported by high-resolution colour imaging capture was performed on the cadaver before formaldehyde embalming. The Perceptron Scanworks V5 3D laser scanner was used to capture accurate data of the surface geometry. Intra-oral scanning was also performed prior to the preservation process to allow accurate reconstruction of dental related anatomy (and to establish key anatomical and clinically relevant key landmarks) when there is pliability/mobility at the temporomandibular joint. The embalming procedure was carried out through collaboration of a mortician and qualified embalmer, supervised by a Licensed Teacher of Anatomy in the Laboratory of Human Anatomy, University of Glasgow. The eyes were injected with a saline solution post-embalming to maintain its life-like contour, a technique established in anatomical and surgical training for ocular (and ocular related) surgical procedures designed by the Canniesburn Plastic Surgery Unit, an international leader in plastic and reconstructive training, research and clinical expertise.

Skin and subcutaneous tissue were meticulously dissected (using standard anatomical techniques) from the head and neck territories with appropriate health and safety precautions typical in the environment of using cadaveric tissue. Superficial muscles, nerves, glands and blood vessels were identified. Scanned muscles and attachments included the sternocleidomastoid, infrahyoid muscles, muscles of facial expression (including those around and within the eyes and nose) and the superficial muscles of mastication, including masseter and temporalis, all of which have important clinical and functional applications. The superficial nerves captured at this stage were the major sensory and motor innervations of the head and neck including the trigeminal and facial nerves, and specifically the termination of the facial nerve onto the muscles of facial expression. Scanned glands included the major salivary glands, i.e. the parotid, submandibular and the sublingual glands, as well as the endocrine thyroid gland. The blood vessels identified at this stage are the facial vessels as well as the jugular venous drainage of superficial anatomical structures.

Deeper dissection of the head included data capture for the training of oral related musculature including genioglossus, geniohyoid, mylohyoid, lateral and medial pterygoids, digastric and buccinators amongst others. These specific muscles are significantly important in oral function, and have immense clinical importance for dental training. The related nerve and blood supply to these structures were captured as previously described.

Neck dissection (down to the thoracic inlet) proceeded deeper to identify and capture major and minor structures at this site. Blood vessels (and related branching) were meticulously dissected to demonstrate arterial supply and venous drainage including the common carotid, subclavian and brachiocephalic trunk. Venous drainage includes internal jugular and subclavian veins, and all tributaries. The relationship of these blood vessels to important nerve structures in the neck demonstrated the close proximity to other structures and included the vagus and phrenic nerves, sympathetic trunk and the brachial plexus in the neck (supplying motor and sensory

Fig. 3.3 Surface mesh generated from raw point cloud data

innervation to the upper limbs), and other closely related sensory and motor innervations. Also the larynx and trachea were included in soft tissue structure identification and data capture to clearly show anatomical relations for important clinical procedures, e.g. cricothyroidotomy, tracheostomy and airway intubation, as well as the oesophagus.

Following every stage of identification of all relevant anatomical structures in the head and neck, Perceptron Scanworks V5 laser scanning supported by 3D mesh processing software package, PolyWorks V12 (which aligns the partial scans and generates a mesh surface) were performed prior to the next, deeper dissection. (Figure 3.3 shows a polygon mesh model generated from raw high-density 3D point clouds). This enabled a complete dataset to be recorded at all stages of dissection, which will then be able to be constructed and deconstructed by users as relevant to the training required, thus creating unique spatial awareness training.

3.3.2.3 Scanning of Skeletal Structures

After soft tissue 3D data capturing, this was removed (apart from ocular structures) to demonstrate the skeletal structures of the head and neck including the neurocranium (calvaria and cranial base), viscerocranium (facial skeleton), mandible and vertebrae. This enables identification of all relevant foramina through which the cranial nerves exit/enter the skull and mandible. Perceptron Scanworks V5 3D laser scanner and PolyWorks were used again to capture the skeletal structures and to process the point cloud data.

Individual laser scans from multiple views of the skull were fused to create a high poly surface mesh, which is the only structure where generated mesh from scan data is directly used in the Head and Neck model. The geometric models of soft-tissue from scan data was found to not accurately represent their natural shape due to soft-tissue deformation resulting from gravity and realignment of the underlying bone structure. Therefore, soft tissue scan data and their mesh are used as a reference in the modelling process and all structures are validated by anatomy specialists to ensure accuracy.

3.3.2.4 Intracranial Scanning

At this stage, the vault of the skull and the brain were removed and the same laser scanning and 3D meshing were performed to record specifically all twelve pairs of cranial nerves, cerebral tissue, including parietal, frontal, temporal and occipital lobes with related gyri and sulci, and cerebral vasculature (e.g. Circle of Willis). Where the cranial nerves have been detached, repeat scanning of the base of the skull was undertaken to allow reconstruction of the full intracranial path of these nerves through the numerous foramina to their termination sites. At this stage the visual pathway was established using the gross anatomy of the optic nerves, optic chiasm, optic tracts with modelling of the lateral geniculate body combined with the previous capture of the midbrain and the occipital cortices. Intracranial vascular circulation was modelled based on standard anatomical and applied surgical knowledge.

After the base of the skull was scanned, the roof of the bony orbit was exposed to capture the extra-ocular muscles namely the levator palpebrae superioris, superior, inferior, lateral and medial recti, and the superior and inferior oblique incorporating their individual nerve supplies, and related vasculature and nerves surrounding these structures in each of the orbits. The cornea, anterior segment and retina were modelled based on existing anatomical knowledge and understanding.

3.3.2.5 Photorealistic Texturing

At each stage, the capture of 3D topographic data through the use of the Perceptron Scanworks V5 3D laser scanning was supported by high-resolution colour imaging. Since cadavers differ considerably in colour and texture from living tissue, and the

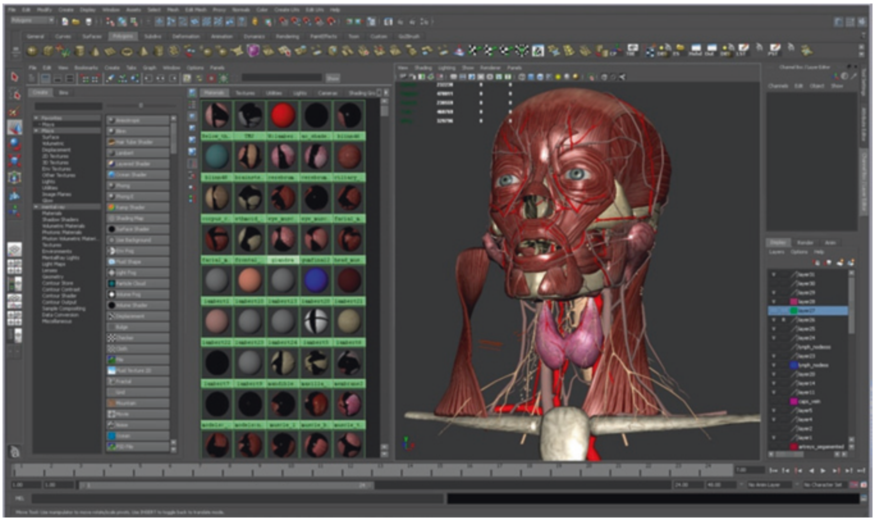

Fig. 3.4 Texturing in Maya

shadow, specular highlights, and occlusions in photographs also make them not suitable for texture mapping [43], the photographic data of soft tissue were mainly used as references when building the geometry of models.

In order to produce a photorealistic and accurate model of the aforementioned structures, the skin surface, muscles and skeletal elements consist of several texture layers, describing colour, glossiness and surface structure subtleties. These were achieved through using a combination of photographs of living tissue, the poly-painting tool in Zbrush, and various other tools in Photoshop and Autodesk Maya. We produced visually realistic organ textures and appearances that are as close as possible the natural colour of skin and healthy living tissue. Figure 3.4 shows work-in-progress texturing in Maya.

3.3.3 The Complete Dataset of Head and Neck

The produced high resolution measured dataset is grouped and identified in Maya in order to serve a wide range of anatomical outputs. This enables the interface to present appropriately tagged data to the user, encapsulated in logical subsets. The tagging process includes clinically relevant, anatomically built structures that present context specific information on a case-by-case basis. A rendered head and neck model showing the muscle, nerve, and vascular layers is presented in Fig. 3.5. The resulting complete dataset does not represent any one specific human body but represents a comprehensive structure that captures and presents a normalised, unbiased anatomical model.

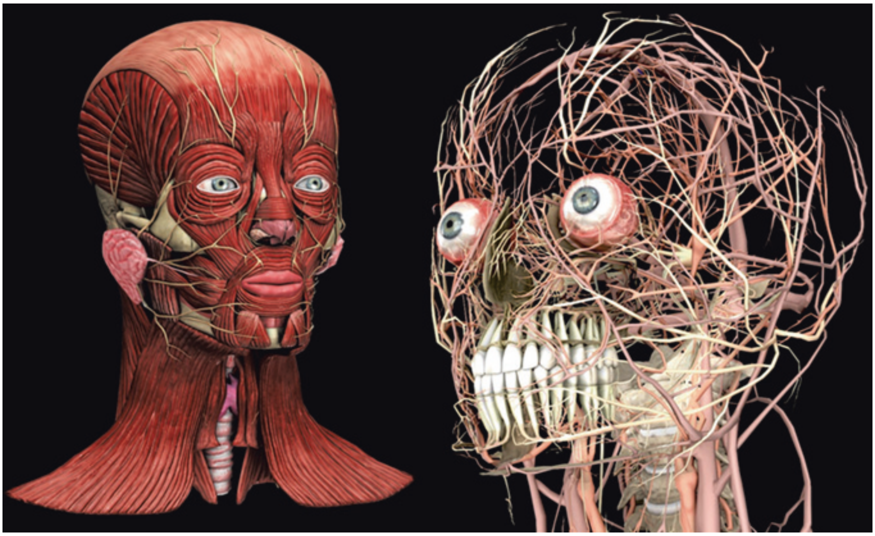

Fig. 3.5 Rendered head and neck showing the muscle, nerve, and vascular layers

3.3.4 Interactive Application

The uniqueness of the DDS model comes from forging together three key components:

- the anatomical precision and accuracy of the constructed datasets;
- the specialist clinical input to challenge and validate the model;
- The interface allowing proficient user-interactivity in real-time, enabling meaningful feedback and learning.

In order to use the head and neck model in a real-time application, low polygon models were created with normal maps baked from a Zbrush sculpt, decimating or re-topologizing in order to simplify the high polygon mesh.

Another importantly unique characteristic is the accompanying suite of manipulation tools, which afford both interactivity (for individual users) as well as interconnectivity (to support collaborative group usage). Figure 3.6 consists of a screenshot of the interactive Head and Neck Anatomy, showing a clipping plane on arbitrary angles and available functions in the vertical toolbar on the right. Apart from basic manipulation (such as object translation and rotation) and navigation controls (zoom, pan, etc.), it provides orthographic clipping planes as well as clipping plane on arbitrary angles. The virtual cutting planes reveal cross-section cuts which resembles cryosection or CT imaging.

The users can interact with the Head and Neck either through conventional input methods or through a combination of Xbox controller and head tracking. Together with passive stereoscopic projection, the latter interface provides an immersive experience for users to explore the internal structure of head and neck.

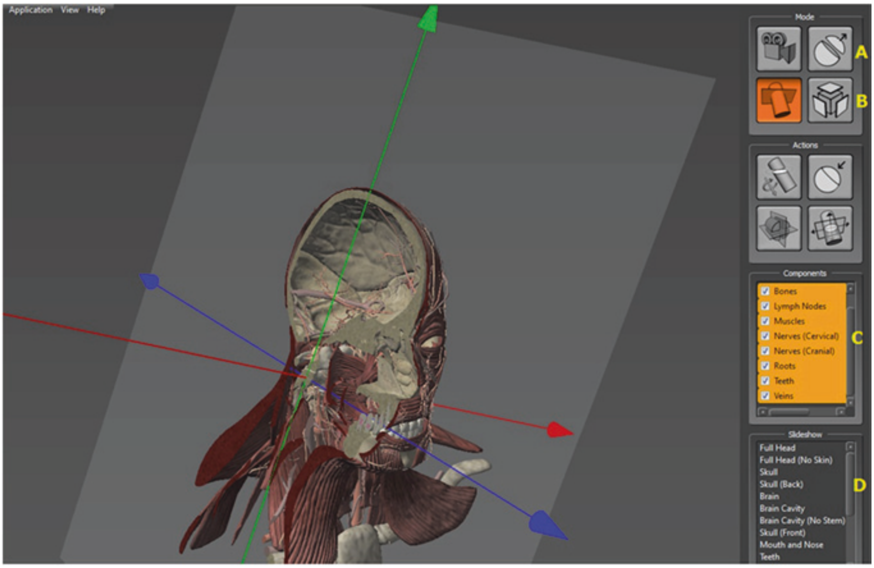

Fig. 3.6 Screenshot of the interactive head and neck anatomy showing clipping plane on arbitrary angles and available features

The user can hide and reveal various anatomical structures, e.g. bones, muscles, nerves, vascular (Fig. 3.6-C), and conduct virtual dissection via a drag-and-drop function (Fig. 3.6-A). An 'explode' mode (Fig. 3.6-B) is available to allow the user to control an explosion via a slider, making the parts separate away from their original locations to reveal the inner details of the head and neck anatomy. Users can also save particular viewpoints and settings which could be loaded in the future (Fig. 3.6-D).

The interactive application also provides data annotation to support teaching and learning. Where clinically relevant, anatomically built structures are appropriately annotated with context specific information on a case-by-case basis to include text related content, linked diagrams and 3D images.

3.3.5 Verification

Working in collaboration with the 3D modelers in the team, every structure which had been dissected was validated during the modelling process, to ensure anatomical accuracy and a true likeness of the human body. The fidelity of the dataset was verified by the project's Clinical Advisory Board which comprised anatomists, clinicians and surgical specialists. Figure 3.7 shows an event of clinical validation. A senior clinical anatomist and government Licensed Teacher of Anatomy, ensured complete anatomical accuracy of all structures constructed in every stage.

Fig. 3.7 The VR training system

The skull and mandible were initially reconstructed from the laser-captured skull. Then, a stringent schedule was created and adhered to at the beginning of the project for creating each and every musculoskeletal, vascular, neural and glandular structure. The approach undertaken was creating each anatomical structure from the deepest (closest to the skull) to the most superficial i.e. the skin (unlike the superficial to deep dissection). As every muscle, bone, nerve, blood vessel and glandular structure was created it had to be moulded around the framework of the skull. This involved using the laser scanned material and also the high resolution digital photography which was captured for all anatomical structures. This ensured direct correlation with every structure to the dissected, laser-scanned and photographed components.

All attachments, origins, terminations and pathway of every anatomical structure were meticulously created, where the anatomist and digital modelers would assign a set of structures to be modeled during a weekly period over the duration of the project. Therefore, this ensured that a catalogue of all anatomical structures in the head and neck was created which had to be modeled from the dissected material. On completion of the modelling of each anatomical structure, this was then reviewed as to its accuracy, initially of that individual element. As the work progressed and the model became more complex, each structure that was created had also to be examined in its accuracy to each and every surrounding anatomical structure. This ensured a completely anatomically correct and robust model was being developed. Where relevant, this was also examined by a clinician who operated in that field to ensure not just exceptionally accurate anatomical datasets were being created, but one with all relevant surgical anatomy clearly and accurately identifiable. This remained crucial where the anatomy of the oral cavity, including the teeth, had to be created to an exceptionally high level of accuracy never seen to date. This involved a team of oral surgeons and senior dental clinicians working side by side with the modelers during the duration of the project. As each anatomical area (e.g. floor of mouth, intracranial territory, orbit etc.) was created in the model, the modelers, anatomist, dental clinicians and surgeons then reviewed those set of structures in that territory and went through a rigorous "signing off" process when the work in that area was complete. To verify the accuracy of the model it was also externally examined and validated by senior academic clinicians specializing in head and neck anatomy. Again, this ensured that each and every anatomical structure gave a real-to-life representation of the structures, as well as ensuring the highest degree of accuracy of the anatomy created.

3.4 Haptic Injection in the Head and Neck Model

One of the most commonly performed procedure by dental practitioner is anaesthetizing the inferior alveolar nerve which runs from the angle of the mandible down the medial aspect of the mandible, innervating the lower teeth, lower lip, chin, and tongue. The successful development of procedural and psychomotor skills that are required for an efficient administration of local anesthesia is a crucial part of the dental curriculum [13]. The training for the psychomotor skill acquisition is traditionally carried out on anatomical models or live patients is critical [35, 44]. Recently, the use of VR simulators has been shown to encourage the learning of sedative procedures in dental education [31]. Although, as mentioned previously in Sect. 3.2, VR simulations presented so far, do not enable the simulation of intrinsic haptic sensations perceived during the realization of the task in the real world. On the basis of outcomes from previous work [6, 8, 17], the implementation of haptic force feedback in VR simulations is believed to enhance the learning of psychomotor skills involved in dental anesthesia injections.

In this section, we present the VR training system enhanced with haptic interaction, which is based on the Head and Neck model that we described in Sect. 3.3 and aims to support the successful development of psychomotor skills that are required in the anaesthetic procedure of the inferior alveolar nerve. The system displays the virtual anatomical head and neck model on which local anesthesia injections can be safely rehearsed aiming the performer to gain in proficiency and self-confidence prior to transition to first injections on live patients.

We use a Phantom Omni device, a cost effective solution for the simulation of realistic haptic force feedback in virtual environments. The Phantom Omni consists of a punctual inter-actuator able to sense position and orientation on 6 DOF input and render forces up to 3.3 N onto 3 DOF output at 1 KHz within a delimited workspace (up to 160 W × 120 H × 70 D mm). A dental syringe represented in the virtual environment is attached to the position and orientation of the stylus of the haptic device (Fig. 3.7). The contact of the needle on soft tissues and teeth, and corresponding haptic sensations (i.e. stiffness, damping, friction) can be perceived through the haptic device. Stiffness and damping force effects are respectively expressed as a function of the depth of penetration x into the touched body and the velocity v of the haptic device. These force effects consider the stiffness and damping properties of the touched body respectively expressed by the variable k and d. These force effects allow defining the normal contact force perceived when the syringe tip is pressed onto a tissue (Eq. 3.1).

$$F = -(k \cdot x - d \cdot v) \cdot N \tag{3.1}$$

where N is the normal reaction force to contact on the touched tissue.

Moreover, when that force exerted on a soft tissue overpasses a threshold, the syringe tip smoothly moves into the tissue and the haptic device simulates the puncture adding haptic sensations corresponding to all traversed tissues along a constraint line corresponding to the contrary normal vector at puncture point. The force effect corresponding to the motion of the syringe tip onto the surface of a soft tissue or a tooth is ruled the computation of friction effect. Friction encompasses static friction and kinematic friction. On the one hand, static friction describes how the body surface remains resistive to motion when no motion of the syringe tip has been engaged. On the other hand, dynamic friction describes how the body surface is resistive to the motion of the syringe tip once it has been engaged. Both friction effects refer to a resistive force to motion which magnitude can be expressed as a function of the normal reaction force to contact as in Eq. (3.2).

$$F_f = \mu_x \cdot N \tag{3.2}$$

where μ_x corresponds to the coefficient of friction of the surface of the touched soft tissue or tooth for each type of friction.

Buttons 1 and 2 of the haptic device can be used to respectively trigger and reset a graphical animation of the plunger pressing the anaesthetic solution for injection. Throughout an injection, the sedated area gradually turns to red (Fig. 3.7).

The VR training system allows assisting the performer while practicing by providing augmented information that could not be obtain throughout the training traditionally conducted in the real world. On the one hand, three additional views of the anatomical head and neck model can be provided through a panel located on the left side of the monitor (Fig. 3.7). The top view corresponds to a depurated view of the inferior mandible which includes the visualization of the inferior alveolar nerve. The middle view shows similar viewpoint but including the parotid glands, the buccinator, the superior pharyngeal constrictor and the medial pterygoid. The bottom view consists of a close-up on the tip of the needle. On the other hand, the system prompts real-time augmented information on performance outcomes in the form of warning messages which highlight a critical position of the needle in soft tissues (e.g. “Your needle is touching a nerve!”, “Your needle is touching a blood vessel!”, “Your needle is close to a gland!”). Moreover, the VR training system can also provide in real-time realistic audio augmented feedback which states for the mood of the patient when the needle insertion procedure becomes painful. According to behavioral psychologists, augmented information feedback is believed to play an important motivational role in the process of skill development [45].

3.5 Conclusion and Future Work

We have described the workflow of data construction, development, and validation of an interactive high-resolution three-dimensional anatomical model of head and neck with haptic interaction. The virtual Head and Neck represents a step change in anatomical construction, validation, visualization and interaction for viewing, teaching and dissemination. Head and neck anatomy is the most complex area of the entire human body. In this very small space, structures of the musculoskeletal, circulatory, lymphatic, nervous, endocrine and integumentary systems are tightly packed. In, for example, the musculoskeletal system, the smallest bones (middle ear: malleus, incus and stapes) and muscles (stapedius, being the smallest, and tensor tympani) of the body are tightly compacted into the petrous temporal bone. This compares starkly with, for example, the lower limb, which has the largest and strongest bone of the body (the femur), the longest muscle (sartorius), and the most powerful muscles (gluteal, quadriceps and hamstrings). With the circulatory system, the only blood supply to the brain passes through the very narrow region of the neck. Without these vessels, the brain would not be perfused, and life would not be compatible. Many other of the body’s finest and most delicate structures are compacted into the head and neck territory. These include the muscles of facial expression, cranial nerves (supplying all head, neck and other structures), brain and spinal cord (and the complexity of the origins of spinal nerves) and bones thinner than paper (lamina papyracea of the ethmoid bone). What we have shown in this project is that even with the smallest structures of the whole body (found in the head and neck), we have managed to successfully acquire data digitally and reconstruct to the most accurate degree so far. As the rest of the body structures are much larger, more robust and easier to dissect, this will be able to be rolled out across all anatomical regions with ease.

In the long term, the results obtained from this three-year project can be viewed as the framework on which to build future efforts. Examples are: to expand models to whole body systems (a project creating a female breast model for breast cancer early detection has already begun); the inclusion of physiological-based animation/simulation; dynamic representations of the progression of diseases; dynamic simulation of deformable soft tissue and physiology, e.g. pulse, blood flow, hemodynamics and elasticity, for haptic display.

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Chapter 4
In Virtuo Molecular Analysis Systems: Survey and New Trends

Guillaume Bouyer, Samir Otmane and Mouna Essabbah

Abstract Understanding the molecules' spatial organization in order to understand their functions is a challenge of recent molecular and structural biology. There are three phases for the analysis of molecular structures and molecular dynamics, and a large number of software. Modeling is the numerical reproduction of the 3D structures, based on biological knowledge and hypotheses. Visualization is the observation and the configuration of the models' parameters. Then, interactions through desktop or Virtual Reality (VR) devices range from spatial manipulation to sensory perception of biological reactions. This can be called in virtuo analysis. It puts the human expert as an actor at the center of the simulation rather than an observer of automatic simulation results. It combines the advantages of computing power and advanced Human-Computer Interaction (HCI) techniques: comfort of natural interactions, physical and psychological immersion, efficiency of multimodal renderings (visual, audio and haptic), etc. This will lead to a fully hybrid cooperation between simulators and experts, for example to overcome algorithmic limits with informal human knowledge and expertise.

4.1 Introduction

Molecular Biology (MB) is a subdiscipline of Biology. It aims at studying the mechanisms involved in the organisation, the functioning and the behaviour of cells at the molecular level. It examines the 3D structures of cells components

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Fig. 4.1 Users interacting with a ribosome in the "C6" platform, built by Mechdyne Corporation for Iowa State University

(e.g. proteins or DNA) and their interactions (e.g. protein docking). Its major industrial outlet is the creation of new drugs.

Indeed, understanding the molecules' spatial organization has become one of the greatest challenges of recent molecular and structural biology. Biologists are trying to identify the link between the 3D structures of molecules, for example proteins or DNA, and their functions.

It is extremely difficult to study molecules in vivo, i.e. in their natural living environment, but also in vitro, for example by microscopic observation, because of their potential lack of stability and the problems to reproduce natural configurations. In silico approaches are a solution: they use computers and algorithms to build 3D molecular models from biological knowledge.

So, MB studies alternate in vivo observations of living organisms, in vitro experiments in controlled environments and in silico simulations performed on computers. These three approaches are closely linked: experiments allow the observation of hypotheses on a biological activity; the resulting data are used to formalize simulation systems and finally these systems are a powerful tool to analyze 3D models bypassing some of the in vitro and in vivo problems. Their capacity to simulate natural phenomena which can not be experimented, offers a big potential and opens doors to further research in the domain.

Accordingly, a large number of more and more precise 3D modeling and analysis systems has appeared. Among these various systems, some are only dedicated to visualization of molecules. Others are more centred on the way of interacting with the 3D models, in order to be able to modify them, in particular through Virtual Reality (VR). It is a scientific and technological field which uses computer science and human–computer interfaces to simulate in a digital environment the behaviour of 3D entities, that one or several users can interact with, in real time (see example in Fig. 4.1).

Interactions and immersion are two key elements of VR experience [8]. 3D interactions (3DI or 3DUI for 3D User Interactions) give the power to users to act on the virtual environment. It is carried out through physical devices called interfaces, which can be sensorial or motor, and software tools or techniques. Three types of natural tasks are classically distinguished in virtual environments [6]:

- Navigation: wayfinding and travel
- Selection: "specifying or choosing an object for some purpose"
- Manipulation: "setting the position and orientation (and possibly other characteristics such as shape) of a selected object"

A fourth task is system control, which is the ability to command or communicate to the system to change either the mode of interaction or the system state.

Immersion can be defined as the feeling of being present in virtual environments, that the virtual world that surrounds the user has replaced the physical world with some degree [6]. This feeling of immersion depends on the user, the application, the devices, etc. The theory is that the user "dives" into the environment to interact directly with the 3D objects or the data rather than being in front of and interact with the system. Kalawsky has adopted a techno-centered classification depending on the type of visual display and field-of-view: Non-Immersive, Semi-Immersive or Fully-Immersive Virtual Environments [38]. The degree of immersion and the efficiency of interactions can also take advantage of the combination of the three main sensori-motor channels: vision, audition and haptic. This is called "multimodality".

In parallel with three decades of enlarging the scope of possibilities (type, size, complexity and realism of environments, precision of interfaces, power of calculators, etc.) some research have focused on usability, comfort and efficiency of interactions, studying the best means to assist the user in his/her tasks.

This chapter presents a survey of 3D molecular analysis. We start by exposing the principles of molecular analysis and the in virtuo approach. We detail each phase of this analysis: 3D modeling, visualization and 3D interactions, and list some systems and applications. Finally we classify these systems and present new trends for molecular analysis.

4.2 From In Silico to In Virtuo Analysis in Molecular Biology

Analysis in Molecular Biology consists in observing biological systems and examining experimental results, in order to understand phenomena in living organisms.

Computer scientists have first been attracted towards Biology with the huge amount of data to analyse. For example, in the beginning of the 70s, there has been the need to list the coordinates of crystallographic structures of molecules, such as proteins (cf. Protein Data Bank[1]). The will to visually represent these data with more and more details and constraints has also attracted computer graphics and modeling specialists [41]. Generated 3D models have now replaced physical "balls and sticks" models. Visualization tools then offer the possibility to display molecular structures and properties in a large variety of representations, each adapted to a type of information (Fig. 4.2). For example, a linear representation (links between

[1] http://www.rcsb.org/pdb/home/home.do

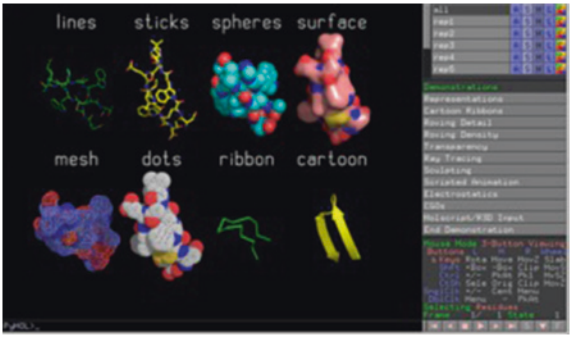


Fig. 4.2 Standard visual representations of molecules (Pymol)

each atom) shows the backbone of the molecule, whereas a surfacic representation displays its outer aspect. In general, visualization softwares also allow to change the point of view, display alphanumeric data, manipulate measurement tools and execute specific calculations (e.g. volume, distance between hotspots, etc.).

However, there is now a need for an improved and deeper analysis, in order to better understand more complex structures and phenomena. It involves more accurate and credible simulations, for example which take into account constraints (geometric, physical, chemical, etc.) or intermolecular behaviours, and the relevant rendering of the resulting data. These data are sometimes not easily viewable, whether because of the size of the molecules (e.g. chromosoms), the "entanglement" of the structure or of course their nature (e.g. a numerical score of electrostatic complementarity). The challenge is then to offer to biologists an efficient perception of these data or, even better, means of interaction with the models.

This is what we call the in virtuo analysis. The expression in virtuo is a neologism proposed in [17] by analogy between the Latin expressions in vivo and in vitro. An in virtuo experiment is conducted interactively by a biologist in a digital environment. It tries to remedy the limits of in vivo and in silico approaches by combining the advantages of numerical simulations and natural interactions. In virtuo analysis is then composed of three fundamental phases: the classical steps of 3D modeling and visualization, and an enhanced 3D interaction phase. which allows the user to animate the model or modify it (Fig. 4.3). The three following sub-sections detail these phases.

4.2.1 3D Modeling

3D modeling consists in generating with a computer a numerical model of a molecule. It translates the information on the components of the molecule (atoms, residues, nucleotides, etc.) into spatial and geometric data (positions, orientations, distances, etc.). The modeling process is generally composed of two steps: the acquisition and processing of experimental data, and the generation in itself. We

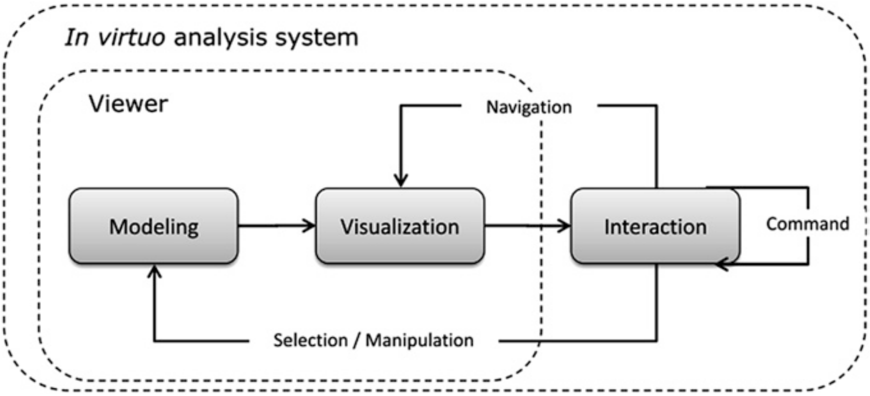


Fig. 4.3 The three phases of in virtuo analysis

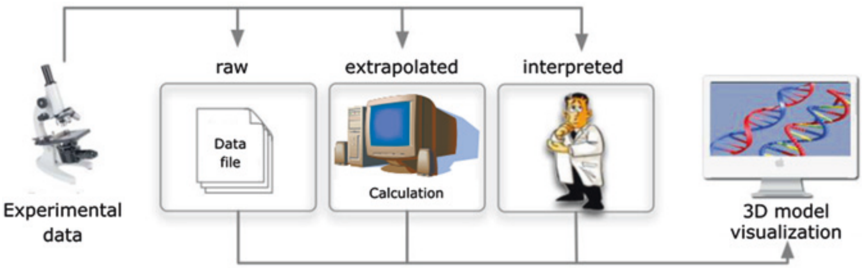


Fig. 4.4 The three main approaches for 3D modeling

can distinguish three approaches for 3D modeling depending on the data they are based on: raw, extrapolated or interpreted (Fig. 4.4).

4.2.1.1 Approach Based on Raw Data

This method is based on real experimental data measured in vitro (rarely in vivo) on the molecule which has to be modeled. It is especially used for mapping proteins. There are two main observation methods to extract 3D information of proteins: Nuclear Magnetic Resonance (NMR) for small molecules, and X-ray diffraction for large ones.

Results obtained are commonly stored in standardized PDB files (Protein Data Bank) (Fig. 4.5). These files include, amongst others, the type and coordinates of each atom that compose the protein. These data can then be viewed in a dedicated 3D software.

```
HEADER    EXTRACELLULAR MATRIX                    22-JAN-98   1A3I
TITLE     X-RAY CRYSTALLOGRAPHIC DETERMINATION OF A COLLAGEN-LIKE
TITLE    2 PEPTIDE WITH THE REPEATING SEQUENCE (PRO-PRO-GLY)
...
EXPDTA    X-RAY DIFFRACTION
AUTHOR    R.Z.KRAMER,L.VITAGLIANO,J.BELLA,R.BERISIO,L.MAZZARELLA,
AUTHOR   2 B.BRODSKY,A.ZAGARI,H.M.BERMAN
...
REMARK 350 BIOMOLECULE: 1
REMARK 350 APPLY THE FOLLOWING TO CHAINS: A, B, C
REMARK 350   BIOMT1   1  1.000000  0.000000  0.000000        0.00000
REMARK 350   BIOMT2   1  0.000000  1.000000  0.000000        0.00000
...
SEQRES   1 A    9  PRO PRO GLY PRO PRO GLY PRO PRO GLY
SEQRES   1 B    6  PRO PRO GLY PRO PRO GLY
SEQRES   1 C    6  PRO PRO GLY PRO PRO GLY
...
ATOM      1  N   PRO A   1       8.316  21.206  21.530  1.00 17.44           N
ATOM      2  CA  PRO A   1       7.608  20.729  20.336  1.00 17.44           C
ATOM      3  C   PRO A   1       8.487  20.707  19.092  1.00 17.44           C
ATOM      4  O   PRO A   1       9.466  21.457  19.005  1.00 17.44           O
ATOM      5  CB  PRO A   1       6.460  21.723  20.211  1.00 22.26           C
...
HETATM  130  C   ACY   401       3.682  22.541  11.236  1.00 21.19           C
HETATM  131  O   ACY   401       2.807  23.097  10.553  1.00 21.19           O
HETATM  132  OXT ACY   401       4.306  23.101  12.291  1.00 21.19           O
...
```

Fig. 4.5 Extract of a PDB sample (http://www.rcsb.org/pdb/files/1mbs.pdb)

However, one of the problems is that this approach uses measurements at a given point in time, which implies static 3D models that can not be modified. Hence, the user can only be an observer of the molecule rather than an active experimenter.

Concerning DNA molecule, raw data are used to model small fragments. Available techniques to measure 3D structure of DNA are for example crystallography, Atomic Force Microscope (AFM) or Cryo-electron microscopy (cryo-EM). Their limits are the necessary small size of the molecule, its potential deformation, and the time and cost of these experiments.

4.2.1.2 Approach Based on Extrapolated Data (or Automatic Approach)

This second approach also uses experimental data, but here they serve as a statistical base and are post-processed to predict the coordinates and the 3D structures of other molecules. This is a standard approach for proteins. Three methods are generally used to generate their structure:

- the homology or comparative modeling [12, 37];
- the protein threading (or fold recognition);
- the ab initio /de novo predictions [48].

Concerning DNA, the generation of the 3D structure is based on geometric statistics on the sequences of nucleotids (A, C, T, G), which have been established

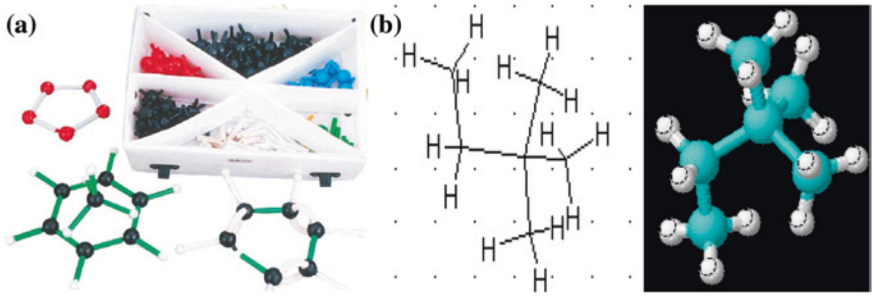


Fig. 4.6 Manual modeling tools. **a** A plastic molecular construction kit. **b** A molecular drawing software (chemsketch)

by biologists from small fragments of naked DNA. This approach is criticized, because to obtain the data the molecule has to be extracted from its natural environment and is distorted. However, large-scale DNA is extremely difficult to study in vitro and even more in vivo. So extrapolated data are a more cost-effective way. Algorithms are time-consuming, but parallel computing now offers real-time processing. Besides, the automatic approach, like the previous one, generates most often static, not modifiable models.

4.2.1.3 Approach Based on Interpreted Data (or Manual Approach)

This approach consists of manually and iteratively assembling the whole model from prior knowledge and experience. The structure is first built on a small portion of the molecule, and then enhanced or rearranged as the previous step is evaluated and valid.

This was the first modeling method available for biologists, which used molecular construction kits in the form of color-coded plastic or metallic parts that snap together to form bonds [21]. Computer tools are now available, for example ACDC/Chemsketch[2] which allows to draw 2D or 3D structures of molecules (Fig. 4.6).

These tools offer a complete freedom to the user, and are particularly useful for teaching, because they require the user to be a full actor in the process, to use his/her knowledge in a continuous human-molecule interaction. The consequence is that the risk for errors is high, and that users are responsible for the validity of the model, in particular for the respect of physical and chemical constraints. This is why they would benefit from an assistance, whether a human expert or an "artificial supervisor", which could guide or even relieve the user of some tasks.

[2] http://www.acdlabs.com/chemsketch/

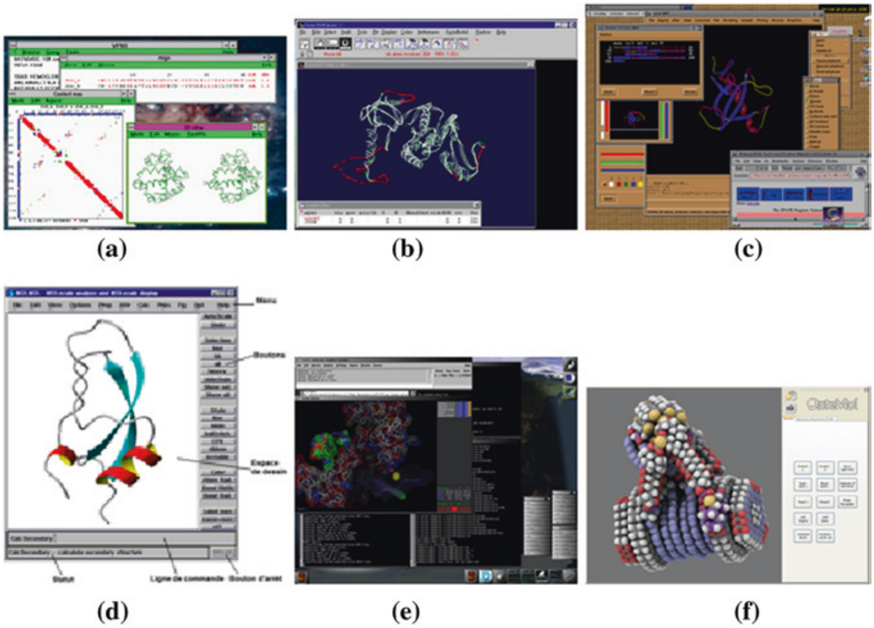


Fig. 4.7 Some examples of PDB-based viewers, by chronological order. **a** WPDB. **b** SwissPDB. **c** Spock. **d** MolMol. **e** PyMol. **f** QuteMol

4.2.2 Visualization

Standard molecular visualization softwares, that we call "viewers", display 3D models of molecules and allow to manipulate them in translation, rotation and scale. Display is monoscopic by default. Various representations are available: lines, spheres, surface, etc. Manipulation and configuration are done using keyboard and mouse.

Viewers are predominantly dedicated to the analysis of proteins. Their main advantage is their ease in use. They can load 3D models stemming from other automatic modeling programs, usually in the form of PDB files from various databases. There is a long list of these softwares. Among them we can cite, in chronological order (Fig. 4.7): PDB (Windows Protein Data Bank) [47], RASMOL/OpenRasMol (RASter display of MOLecules), Swiss-Pdb Viewer[3] [30], Spock (Structural Properties Observation and Calculation Kit) [11], MolMol (Molecule analysis and Molecule display) [49], PyMOL [16], Discovery Studio,[4] QuteMol [54]. Besides their common properties, some viewers add extra functionalities. Swiss-Pdb Viewer allows additional calculations, QuteMol stresses the quality of visual real-time rendering

[3] http://spdbv.vital-it.ch/

[4] http://accelrys.com/products/discovery-studio/index.html

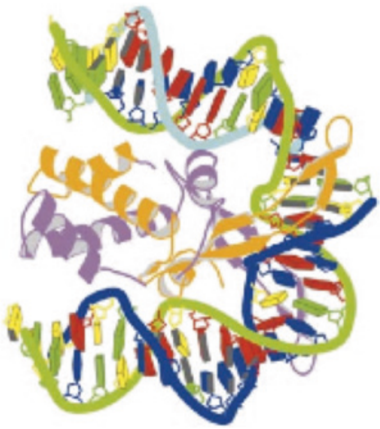


Fig. 4.8 3D modeling of DNA in 3DNA [42]

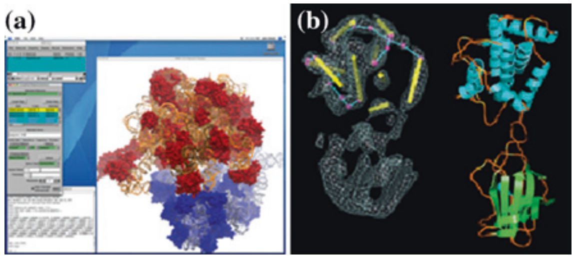


Fig. 4.9 Two systems for modeling and observation of molecular dynamics. **a** VMD. **b** Chimera

(high resolution, shadows, etc.) and animation. Support for stereoscopic rendering has been added in RASMOL [36].

Softwares dedicated for DNA 3D structure analysis are rarer. 3DNA (3-Dimensional Nucleic Acid structures) [42] can manipulate simple, triplex, quadruplex structures and other patterns from a PDB file (Fig. 4.8). It is based on extrapolated data.

Finally, some viewers are dedicated to the simulation, the animation and the analysis of molecular dynamics. VMD (Visual Molecular Dynamics) [9, 35] is one of the first systems designed for the analysis of large molecular systems (proteins, nucleic acid, lipids, etc.). One of its characteristics is to allow remote use. It is also compatible with 3D interfaces, haptic rendering and numerous displays (Fig. 4.9). YASARA (Yet Another Scientific Artificial Reality Application)[5] can be used in several scientific domains, in particular molecular dynamics. Compatible devices go from autostereoscopic desktop screens to large active stereoscopic projection systems, and 3D interfaces. In the same category, gOpenMol[6] [4] permits the display of molecular orbitals, electron density and electric potential energy, and can

[5] http://www.yasara.org

[6] No longer supported.

Fig. 4.10 Levinthal's interactive molecular visualization system [41].

create VRML files. Qmol[6] [22] provided stereo rendering. CHIMERA [44] is dedicated to the analysis of protein docking and supramolecular architectures (Fig. 4.9). Molekel [56] can generate with custom parameters (bounding box and resolution), then display with programmable shaders and animate several types of surfaces (orbitals, iso-surfaces, van der Waals, etc.).

4.2.3 3D User Interaction

There is a second category of molecular analysis systems, which include the third phase of 3D interaction [19] and which we call "in virtuo" analysis systems. They offer different degrees of immersion, depending essentially on the visual displays and interaction devices. Visual immersion varies mainly according to the size and number of screens, and the use of active or passive stereoscopic rendering. Interactions tend to be natural and multi-sensorial with the use of VR technologies.

Indeed, the manipulation of 3D molecular models with a desktop mouse and keyboard (2D devices) is sometimes difficult. 3D devices like trackball, 3D mouse or flystick turned out to be more efficient for navigation, selection or manipulation tasks [1]. With the integration of these devices, molecular analysis systems allowed their users to go beyond the simple observation of the models and to naturally, intuitively interact with the data. It should be noted that new visualization and interaction means for molecules do not imply necessarily a change in 3D modeling. Actually, most of the systems mentioned in this section use similar models and visual representations as existing viewers (VMD, YASARA, PyMol, etc.) (Sect. 4.2.2).

4.2.3.1 VR Interactions

The first interactive molecular visualization system was developed in 1965 by Levinthal [41]. It allowed a user to command the orientation and speed of a molecular 3D model with a trackball (Fig. 4.10). By using a lightpen on the screen it

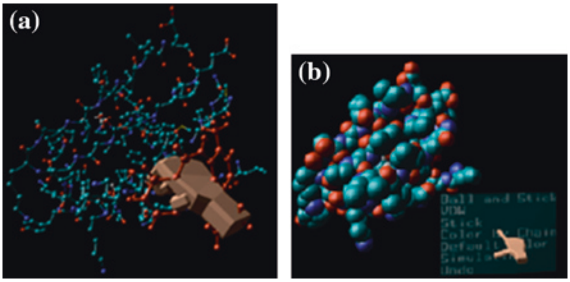


Fig. 4.11 RealMol system [1]. **a** Molecules can be selected and manipulated with a data glove. **b** Choice made on a 3D menu

Fig. 4.12 Atoms dynamics in MolDrive [39]

was also possible to select an object within a menu or to zoom in specific part of the molecule. More and more immersive systems have been developed since then. For instance, VRMol [31] was built to study molecules' characteristics in an immersive way. It is composed of a 3D mouse, a data glove and a large screen for stereoscopic projection. Selection is done by pointing. Hand gestures control a menu for visualization choices. In the same way, RealMol (Real-time Molecular dynamics simulation) [1] was developed for interactive molecular modeling and dynamics simulation (Fig. 4.11). It offers total visual immersion in a CAVE (Cave Automatic Virtual Environment) or a HMD (Head-Mounted Display). However, it can also be used on desktop platforms for the sake of usability. MolDRIVE (Molecular Dynamics in Real-time Interactive Virtual Environments) [39] allows dynamic and interactive simulation on a stereoscopic table with a 6-DOF tracker. Standard molecular visual representations are enriched with other graphical modalities: 3D vector, spring, cursor, sphere, etc. (Fig. 4.12).

ADN-Viewer [28] (Fig. 4.13) is a software which generates a 3D structure of DNA molecule based on extrapolated data. Then it allows immersive visual exploration with a genomic or genic representation on two large stereoscopic screens. Interaction is done with a Wand.[7] Navigation in the scene and selection of DNA parts with a virtual ray are possible.

[7] A Wand is a 6 degrees-of-freedom device with a position/orientation tracker, 2 buttons and a trackball.

Fig. 4.13 A user showing interesting structures of a DNA sample with ADN-viewer [28]

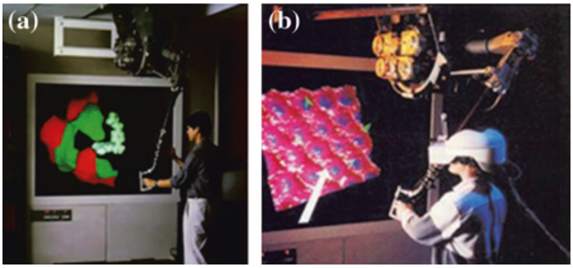


Fig. 4.14 The GROPE-III system [7]

4.2.3.2 Haptic Rendering

In addition to the use of the visual immersion, the haptic modality is naturally applied to biological analysis to provide multisensory perception. It is mainly used for protein-ligand docking analysis.

The first system to allow visual and haptic exploration of molecules was GROPE-III [7]. Visualization was done through a stereoscopic HMD. Haptic interaction (e.g. surface perception, vibration, etc.) used a 6-DOF ARM (Argonne-III Remote Manipulator) and a Nanomanipulator [55] for a better precision (Fig. 4.14).

Bayazit et al. [3] used robotics motion planning techniques for molecular docking. The user manipulates a rigid ligand molecule and tries to locate binding sites on the protein by feeling potential energy thanks to repulsive forces provided by the haptic device. This is especially efficient to find corridors. The user can also investigate a path or roadmap generated by the automated planner.

IMD [52] provides real-time feedback and steering for molecular dynamics simulations of biomolecules. It uses VMD software for visualization and NAMD program for molecular dynamics. Physical forces generated by the user's hand are translated into forces on simulated atoms. Resulting data can be gathered for analysis.

CAMD (Computer-Aided Molecular Design) [40] is a system for molecular docking and nanoscale assembly (Fig. 4.15). Manipulation is done with a 5-DOF electro-mechanical custom device. It helps the user in identifying whether a flexible ligand can be docked or assembled into a rigid receptor by rendering the

Fig. 4.15 CAMD [40]

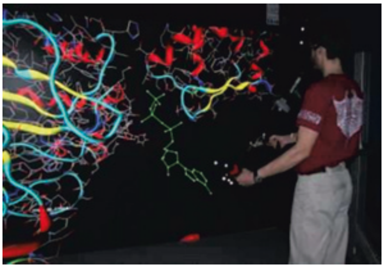


Fig. 4.16 Immersive and haptic docking in Daunay et al. [14] (ligand in *green*) (Color figure online)

potential van ver Waals energy. A 3D grid method is used to calculate the potential energy and force in real-time. A second 3D grid is used to pre-compute the list of possible colliding receptor atoms to speed up collision detection. The ligand can also change its geometric conformation depending on stability.

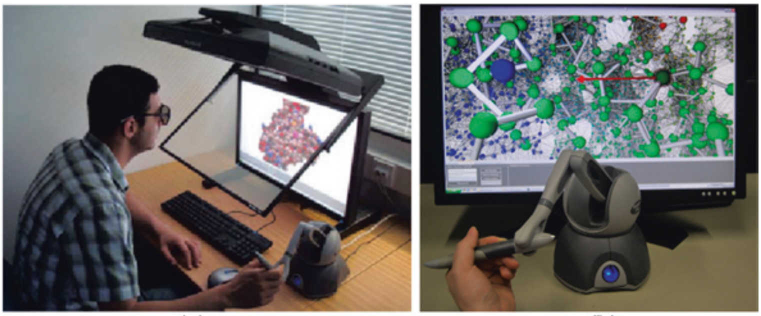
Daunay et al. [14] proposed a method for haptic rendering of protein-ligand docking. It aims at being compatible with any molecular simulator based on a force field minimization process. It has been tested in immersive conditions (Fig. 4.16).

Subasi and Basdogan [53] showed the efficiency of haptic rendering to accelerate the binding process and reduce the errors. The user manipulates a ligand and explores the potential binding sites on the protein. Grid-based van der Waals and electrostatic interaction energies are rendered with attraction and repulsion forces.

Bidmon et al. [5] designed a system for evaluating the anisotropic motion of proteins with time-based haptic feedback. The user can select and lock the probe to an atom to feel its conformational path with movement. It is also possible to touch the proteins in various representations and with different surface characteristics (e.g. friction depending on the type of the atom). Stereoscopic visualization is based on VMD.

HaptiMol ISAS[8] [51] enables users to interact with the solvent accessible surface of biomolecules, by probing the surface with a sphere. HaptiMOL ENM

8 http://www.haptimol.co.uk



(a) (b)

Fig. 4.17 HaptiMol [51]. **a** HaptiMol ISAS: stereoscopic visualization and haptic exploration of a molecule. **b** HaptiMol ENM: forces applied to atoms

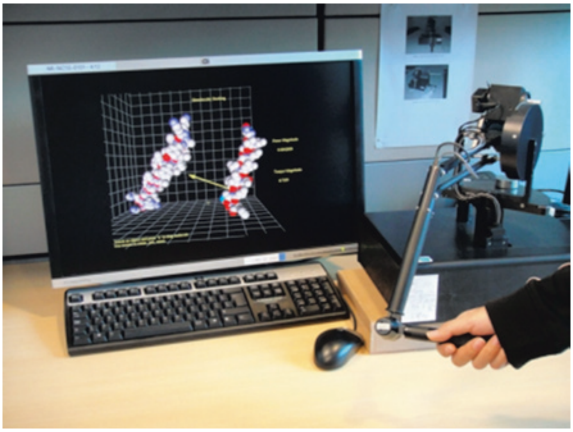


Fig. 4.18 HMolDock system [34]

allows forces to be applied to atoms of an elastic network model, using a haptic device (Fig. 4.17).

Hou and Sourina proposed HMolDock (Haptic-based Molecular Docking) (Fig. 4.18), a visual-haptic system for helix-helix docking research and applied it for e-learning [50]. They improved it with force and torque haptic rendering algorithm [34]. The Lennard-Jones potential is used to find the optimal binding position and orientation of a ligand with a receptor. The user can change the attach position on the ligand to change the torque feedback. Multi-user collaborative docking is also possible with two devices (a 3-DOF and a 6-DOF).

The goal of the FvNano project[9] is to provide an easy to use virtual laboratory to manipulate and visualize molecular systems on high-performance computing

[9] http://www.baaden.ibpc.fr/projects/fvnano/

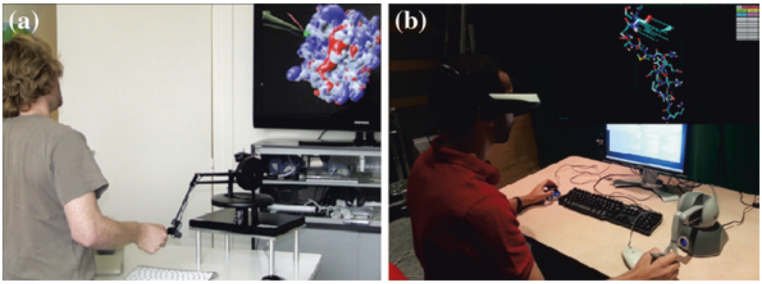


Fig. 4.19 The FvNano project. **a** Typical working session with monoscopic display and haptic interaction. **b** Immersive working session with stereoscopic rendering in HMD and haptic interaction

platforms. It uses molecular dynamics software for simulating flexible protein docking in real time, in particular to understand molecular motions inside a protein structure. A spaceball is used to move the viewpoint and haptic arms to manipulate the molecular structures, while rendering the bound forces [15]. Bimanual haptic manipulation is also supported. Experiments have been conducted using different displays (stereoscopic CRT, high-resolution LCD and large HD LCD, HMD) (Fig. 4.19).

IGD (Interactive Global Docking) [33] aims at completing existing automatic docking procedures, which can report false positives, with knowledge-guided interactions. Stereoscopic displays combined with head-tracking and haptic rendering are used to help solving docking problems. An offline exhaustive search is first used to pre-compute a 3D field of fitting scores around a protein. The user can then move the probe with a haptic interface and be guided to optimal positions and orientations. Additional real-time information (favorable protein-protein distances and potential clashes) are also provided with visual cues. The systems is compatible with stereoscopic rendering, head-tracking and multiple haptic devices.

We can note than most of these systems use grids, approximations or simplifications for the calculations to be compatible with real-time haptic rendering.

4.2.3.3 Audio Rendering

The audio modality is rarely used alone to enhance visualization. Garcia-Ruiz and Gutierrez-Pulido [26] have conducted a survey of research on auditory display techniques in HCI and especially the use of non-speech sounds in chemical education. A potential benefit of audio-visual combination is the enhancement of engagement and learning. The same authors have previously proposed the use of earcons to represent data of amino acids [23, 24] or to identify each of the four bases of a DNA molecule [27].

Fig. 4.20 ILS: evaluation procedure with SPIDAR-G [46]

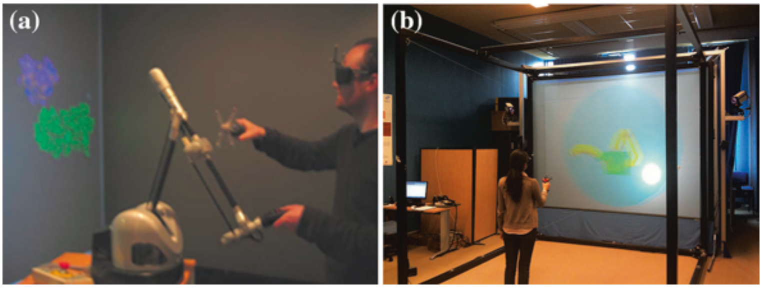


Fig. 4.21 Two multimodal and immersive systems. **a** Interactive system for protein docking in the CoRSAIRe project [20]. **b** Chromatin fibre immersive deformation [18]

4.2.3.4 Fully Multimodal Rendering

Finally, other systems combine interactions on the three major sensori-motor channels: vision, hearing and haptics.

ILS (Intermolecular Learning System) is an interactive teaching-aid to understand molecular interactions [46] (Fig. 4.20). Haptic rendering allows the user to feel van der Waals and electrostatic forces between two molecules. The effectiveness of this environment has been evaluated on a group of students, in addition to a real lecture. The CoRSAIRe project (Combination of sensori-motor rendering for the immersive analysis of results) [20] has the same objectives as IGD: combining automatic and interactive methods for docking problems (Fig. 4.21). Visualisation is based on Pymol. Visual immersion is provided by a stereoscopic CAVE with head-tracking, and audio immersion by spatialized rendering on headphones or a set of eight speakers. Bimanual manipulation of molecules is done with a haptic arm Virtuose and a 3D mouse. The user tries to fit together two proteins and perceives their geometric and physico-chemical compatibility. Essabbah et al. [18] proposed a system for the interactive deformation of DNA structures (chromatin fibre). Visual, haptic and audio guides assist the user in order to respect biophysical constraints (Fig. 4.21).

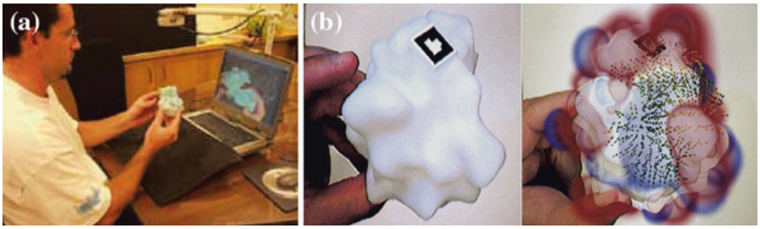


Fig. 4.22 Molecular analysis with tangible AR interface [29]. **a** Set-up. **b** Real-time volume rendered electrostatic field displayed around the protein physical model [29]

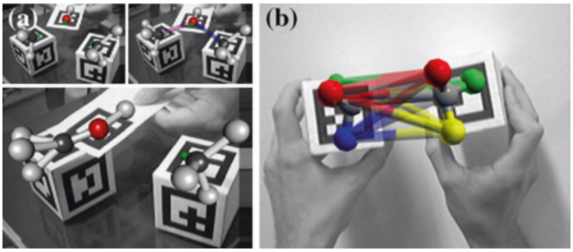


Fig. 4.23 Molecular analysis with bimanual AR interface [43]. **a** Visualization of a dynamic interactions between two molecules. **b** Display of potential bonds between pairs of atoms on two molecules

4.2.3.5 Augmented Reality

Tangible interfaces and marker-based Augmented Reality (AR) techniques can also be used for analysis. For example, 3D models of molecules can be projected on physical models (obtained with 3D printers) combining real natural manipulation with computer generated information (different visual representations, physico-chemical properties, dynamics, etc.) which users can command [29] (Fig. 4.22). Another system allows tangible bimanual manipulation of molecules, with visual feedback of potential bonds and dynamic structural changes. Bonds can be selected using two gesture-based techniques [43] (Fig. 4.23).

4.2.3.6 Natural User Interfaces

Natural User Interfaces (NUI) [57] rely on devices that are either invisible, unobtrusive or intuitive to the user. They refer for example to voice command, gesture recognition, touch input, etc. One goal of NUI for molecular analysis is to release experts from the technical aspects of commands (e.g. the use of keyboard shortcuts), in order to concentrate on the task. The use of gesture recognition for

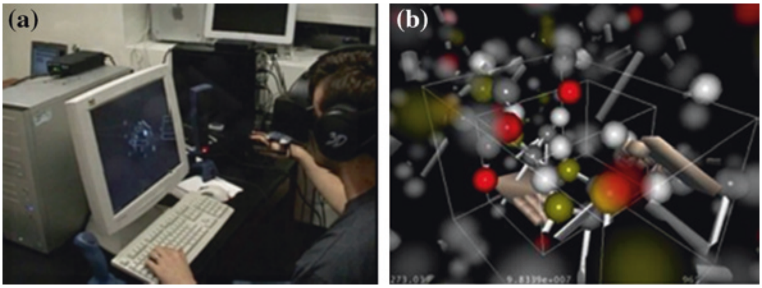


Fig. 4.24 AMMP-Vis [10] (**a**) 3D interaction (**b**) cooperation between two users

interacting with virtual objects has particularly spread through recent and affordable consumer products, such as Microsoft Kinect or Leap Motion sensors, that can be connected to existing molecular viewers. A number of demonstrators are visible online, e.g. the manipulation of crystallographic models[10] or the Molecular Playground.[11] Speech recognition is rare. A preliminary study has been carried out to command three different molecular representations of an amino acid [25]. A promising Molecular Control Toolkit is developed by Sabir et al. [45] to provide generic gesture and speech recognition functionalities to existing viewers.

4.2.3.7 Collaboration Tools

The next step after multimodal interaction is often collaboration. NAVRNA [2] is a multi-surface and multi-user system for RNA analysis. It allows two simultaneous and correlated displays (2D secondary structure on a table, 3D tertiary structure on a wall). Interactions consist in manipulating tokens tracked by a computer-vision system. AMMP-Vis (Another Molecular Modeling Program—Vis) [10] is a virtual collaborative environment for local and distant 3D molecular modeling. Selection and manipulation are done using data gloves, and navigation with a joystick (Fig. 4.24). It also allows to visualize in real-time the results of a molecular dynamics simulator and to share views depending on the needs of each user. We can also cite Foldit[12] [13], a famous multiplayer online game aiming at crowdsourcing protein design and protein structure prediction. Interactions are done with classic desktop keyboard and mouse, but visual cues are efficient to understand folding constraints, and the 3D models are highly modifiable.

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[10] http://www.utdallas.edu/hnam/software.php

[11] http://molecularplayground.org

[12] http://fold.it

4.3 Discussion

As we have seen above, there is a large number of existing molecular analysis systems, dedicated to proteins or DNA studies. Some systems can be called viewers. They allow the visualization of 3D models and biological data. Most of them are free or even open-source and easily accessible thanks to usual 2D interfaces (keyboard, mouse, menus, etc.). They are an efficient tool for rapid modeling and analysis of a molecule, either to illustrate a document or confirm an hypothesis. However interactions and visual exploration stay limited. On one hand, if 3D interaction with 2D devices is now well known, it is not natural and requires cognitive efforts from the biologist. On the other hand, the size and type of the display are not always adapted to observe complex 3D structures. Finally, the models are most of the time non-modifiable.

This is precisely these limitations that are tackled by in virtuo molecular analysis systems, which allow additionally 3D interactions with these models and data, to reach a more natural experience. Some of them are also characterized by visual immersion and the use of multiple modalities.

Viewers are more numerous than in virtuo systems. This can be explained by the fact that VR techniques appeared more recently than 3D visualization techniques and that they require more expensive and voluminous platforms. The following sections discuss the in virtuo systems that we have identified in this survey.

4.3.1 Classification According to Visual Immersion and Multimodal Rendering

We have classified these in virtuo systems according to the visual immersion they provide and the sensori-motor channels they use (Table 4.1).

We are considering two criteria for visual immersion in this study: the field of view and the existence of stereoscopy. The field of view is theoretically easy to increase by changing the size of the display (e.g. move from a desktop screen to a human-scaled projection system). On the contrary, adding multiple screens (e.g. CAVE) is more difficult and depends on the hardware and software architecture. Similarly, allowing stereoscopic rendering depends on the devices (compatible graphic card and displays) and on the software, which must be capable of calculating and rendering left and right images. As a consequence, we distinguish between “non-immersive” and “immersive” systems according to their capacity to provide stereoscopic rendering or visual display on several adjacent large screens (this definition could be inappropriate in other contexts). Stereoscopic rendering offers depth cues to the scene and allows a less ambiguous observation of complex 3D structures, both at global and local level. Multi-screen display increases both field of view and field of stereocopic view, and allows multi-user exploration.

Table 4.1 Classification of interactive molecular analysis systems according to their level of visual immersion and their use of multimodality

Molecular systems	Modalities		
	Visual display	Haptic rendering	Audio rendering
Non-immersive and visual rendering only			
Levinthal [41]	Monoscopic desktop screen		
Immersive and visual rendering only			
VRMol [31]	Stereoscopic large screen		
RealMol [1]	Stereoscopic large screen		
ADN-Viewer [28]	Stereoscopic large screen		
MolDRIVE [39]	Stereoscopic large screen		
AMMP-Vis [10]	Stereoscopic desktop screen		
Non-immersive and multimodal rendering			
Bayazit et al. [3]	Monoscopic desktop screen	Potential energy, path (PHANToM)	
IMD [52]	Monoscopic desktop screen	Feedback and steering for dynamics	
CAMD [40]	Monoscopic desktop screen	Potential energy, collisions (5-DOF device)	
Subasi et al. [53]	Monoscopic desktop screen	Intermolecular forces (limited workspace device)	
ILS [46]	Monoscopic desktop screen	Intermolecular forces (SPIDAR)	
HMolDock [34]	Monoscopic desktop screen	Intermolecular forces and torques	
Immersive and multimodal rendering			
2 GROPE-III [7]	Stereoscopic large screen	Collisions (ARM)	
Daunay et al. [14]	Stereocopic large screen	Intermolecular force field (virtuose)	
Bidmon et al. [5]	Stereocopic desktop screen	Protein surface, atoms dynamics (PHANToM)	
HaptiMol [51]	Stereoscopic desktop screen	Solvent accessibility, atoms dynamics (PHANToM)	
FvNano	Stereoscopic desktop or large screen or HMD	Flexible docking	
IGD [33]	Stereoscopic screen + head-tracking	Haptization of a precomputed 3D field of score	

(continued)

Table 4.1 (continued)

Molecular systems	Modalities		
	Visual display	Haptic rendering	Audio rendering
CoRSAIRe [20]	Stereoscopic large screens + head-tracking	Collisions + haptization of a numerical score (virtuose)	Collisions + auralization of a numerical score
Essabbah et al. [18]	Stereoscopic screen	DNA constraints exceeding (Spidar)	DNA constraints exceeding

Then we use the term "multimodality" to describe the use or the combination of more than one sensori-motor channel (vision, hearing and haptics) to interact within the virtual environment. Haptic rendering is mainly used to communicate intermolecular forces and collisions information between the molecules, especially for ligand-protein docking analysis. Audio rendering is rarely used (the most advanced feedbacks are in CoRSAIRe).

4.3.2 Contribution of VR Techniques for Molecular Biology

Table 4.2 sums up the devices and techniques used within the previous in virtuo systems for each 3DUI task.

We can first notice that manipulation is a central activity. It allows to intuitively modify the structure, to move some parts, or to add forces and study dynamics. It is done using either desktop-based devices adapted to 3D environments (3D mouse, joystick), VR devices (data gloves, tracking) or haptic devices. Manipulation can be done only on specific objects that have been previously selected. So selection techniques are common in these applications, and often done with the same devices as manipulation. Interaction techniques are standard and easily accessible: virtual hand or virtual raycasting. The common principle of these studies is, beyond observation, to offer human-scale, direct manipulation of "realistic" molecular models, as if biologists had molecules in hands and could observe them and naturally experiment their ideas.

On the contrary, navigation (in the sense of displacement) is unusual. In fact, the virtual scene is often composed of only one or two objects (the molecules) and does not need for a wide exploration. The observation of these molecules can be done by manipulating them along 6 degrees-of-freedom.

The setup of parameters or the changes between tasks are done generally with a 3D menu and a selection or pointing device (e.g. VRMol or RealMol) or buttons, if any, of the manipulation devices. Complex commands (query, save/load, etc.) always need for additional device such as keyboard.

Table 4.2 Details of available 3DUI tasks and devices in some identified in virtuo molecular analysis systems

Molecular systems	Devices or techniques used for VR tasks			
	Navigation	Selection	Manipulation	Control
Levinthal [41]		Optical pointer	Trackball	Optical pointer + menu
VRMol [31]	Data glove	3D mouse + virtual hand	Data glove + virtual hand	Menu
RealMol [1]		Data glove	Data glove	Menu
ADN-viewer [28]	Joystick + magnetic tracking	Joystick + virtual raycasting		Menu
MolDRIVE [39]		6-DOF marker-based traking	6-DOF marker-based traking	6-DOF marker-based traking
AMMP-Vis [10]	Joystick	Data glove + virtual hand	Data glove + virtual hand	Button of the joystick
ILS [46]			6-DOF haptic device (Spidar) (+ keyboard)	
HMolDock [34]		6-DOF haptic arm (PHANToM)	6-DOF haptic arm (PHANToM)	
GROPEIII [7]		6-DOF haptic arm (ARM)	6-DOF haptic arm (ARM)	Button of the haptic arm
Bidmon et al. [5]		6-DOF haptic arm (PHANToM)	6-DOF haptic arm (PHANToM)	Button
Hapti-Mol [51]	6-DOF Haptic arm (PHANToM) + adapted bubble technique	Haptic arm	Haptic arm	
Fv-Nano	Spaceball		Haptic arms (PHANToM)	Keyboard
IGD [33]	Head tracking		Haptic arm (6-DOF PHANToM or 3-DOF Novint Falcon)	Button
CoRSAIRe [20]	Head tracking		6-DOF haptic arm (Virtuose) + 3D mouse	Menu, console, keyboard
Essabbah et al. [18]	Joystick button	3-DOF haptic device (Spidar) + virtual hand or joystick + virtual raycasting	3-DOF haptic device (Spidar) or joystick + virtual hand	Joystick buttons

Besides the desired naturalness of the interactions, other benefits come from VR techniques in the form of multimodal rendering. It allows a distribution of information on two or three separate sensorial channels, which can potentially:

- increase the number of communicated data (3D scenes in molecular biology can reach a huge amount of information);
- increase the quality of perception of these data. Indeed, each channel is adapted to a kind of stimulus: vision is powerful for spatial relationships (e.g. topologies of proteins surface for docking); haptics is specialized in the perception of shapes, movement and forces (e.g. electrostatic interactions, physical collisions); audition is adapted to the rendering of ponctual events (e.g. alerts) or time-dependent signals (e.g. the variation of numerical data);
- decrease the overall cognitive load and create a feeling of presence [32], which could improve the confort of the efficiency of the user.

A VR platform is also a support for communication and collaboration: it allows to gather several actors of a same project around a comprehensible and common representation of a problem.

4.3.3 Towards a Hybrid Approach

Besides the previous benefits, one of the potential contributions of VR for the analysis of molecules is to compensate some drawbacks of automatic approaches. Indeed, some simulation algorithms require too much time or calculation resources, and produce too many or incorrect solutions. Moreover, some knowledge (e.g. biologist's expertise) are difficult to integrate or translate into modeling or generation programs.

One of the solutions is to allow the user to intervene sooner in the process rather than just observing the results, and to express naturally his/her knowledge with direct interaction on 3D models (e.g. to move closer together two distant genes). This hybrid process between automatic calculation, and immersive, multimodal interactions could reduce the calculation time and the risk for models lacking in credibility.

The scientist alternates automatic and interactive phases depending on his/her needs (Fig. 4.25). The first step is associated to the modeling process, it generates a preliminary 3D structure via a geometric engine. Then, visual, audio and haptic renderings are used to explore the model and natural interactions allow the user to improve it or to add some knowledge to the environment, based on his/her expertise. Interactions have to be the tools to translate the mental images of the expert. Finally the user can restart the automatic process by taking into account the changes made in the virtual scene. It can for example reduce the size of the search space.

The systems proposed by Subasi and Basdogan [53], Heyd and Birmanns (IGD) [33] and Férey et al. (CoRSAIRe) [20] are a perfect illustration of this growing tendency.

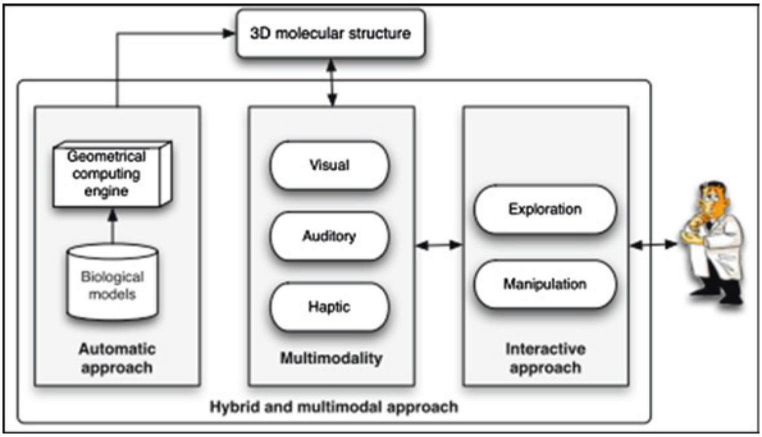

Fig. 4.25 A hybrid and multimodal approach for assisting molecular analysis [18]

4.4 Conclusion

This survey of research and developments conducted on 3D molecular analysis systems has shown invariant features and emerging trends thanks to further progress in Molecular Biology, Computer Science or Virtual Reality.

The main function of molecular analysis systems is the visualization of generated 3D structures and simulated biological data. Modeling algorithms are either integrated in analysis systems, or independent. Their results are used mainly in the form of data files. There are numerous visualization software called "viewers" which allow simple keyboard and mouse interactions to observe the molecules. Current research is turned towards real-time computation of molecular data or dynamics simulation, and high-performance and high-quality visual rendering (e.g. with parallel computing or GPGPU).

There is also a crucial need for enhanced and more natural interactions. Some systems integrate Virtual Reality devices and techniques to respond to this need, creating useful Human-Molecule Interactions. We call this in virtuo molecular analysis. We have proposed a classification of these systems based on their level of visual immersion and their use of multimodality. Visual immersion is very well managed with stereoscopy and large screens, so are standard 3D interactions. The use of haptic rendering is widely studied and is now stable for forces and torques. These systems have demonstrated their benefits in order to facilitate the manipulation and to better understand complex phenomena and 3D structures.

A next step is the transition from this quite linear process Simulation—Visualization—Interaction to a hybrid approach where all phases are closely interlinked, where biologists could interact naturally and intervene in the automatic process by bringing their personal knowledge. This hybrid approach requires modifiable models, efficient tools for interacting with them and smooth combination of calculation and interactions. One of the promising line of research concerns multimodal interactions (which are also applicable to other scientific domains with complex data). Visualization and haptisation, but also auralization of data could be rendered in real time during the simulation. The combination, substitution and redundancy of modalities should be studied to bring novel assistance tools for 3D data analysis.

Finally, given that the very nature of science is collaborative, there is still a lack of tools for co-located and distant collaborative work.

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Chapter 5
Kinect-based Gesture Recognition in Volumetric Visualisation of Heart from Cardiac Magnetic Resonance (CMR) Imaging

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Abstract Heart attacks increase rapidly as a killer disease at Malaysia, therefore Malaysian government give more attention to this particular disease in order to reduce the number of patients who got cardiac disease. Based on Malaysia Noncommunicable Disease survey during 2005–2006 and National Strategic Plan for Non-Communicable Disease (Medium term strategic plan to further strengthen the cardiovascular diseases and diabetes prevention and control program in Malaysia (2010–2014), Disease control division, Ministry of Health, Malaysia, 2010 [1]), there are several cause of cardiac disease such as less 60.1 % lacking on physical exercise, 25.5 % come from bad habit of smoking, 16.3 % patient suffer from overweight and 25.7 % from high blood pressure. For that reason, early medical diagnosis and treatment is very important for reducing the growth of heart patient. The 3D medical visualization is one of technology that potential and attractive for patient, medical doctor and scientist. Interaction with medical visualization is one of attractive research topics in human computer interaction and medical visualization. Controlling the volume visualization for 3D heart is one of the useful applications for clinician to produce an efficient ways on analysing the behaviour of heart. The aim of the this paper is to build a virtual human heart from medical imaging data, together with an interactive interface using visual 3D holographic, haptic and sonic feedback. The blood flow of human reveals the functionality of cardiovascular circular system. Therefore, the precise information retrieval and visualization display of blood flow is really needed in medical field.

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5.1 Introduction

Heart diseases are one of major death causes in Malaysia. Early diagnosis of this disease can helps doctor to save patient lives. In recent years, many non-invasive imaging techniques such as that been developed by Narici [2] which can be used to help diagnosis process of analysing data generated such as CT, MRI, PET and ultrasound. The common method that always been used to view these data are using DICOM Viewer. Usually, these data been visualized from slices of set images and it allows the user to explore the surface of 3D model that generated by DICOM viewer. One of the challenges in visualization of the dataset is to provide clinicians with a more realistic view of patient's body anatomy especially for the heart. In order to give users a deep sense of presence into the virtual scene and experience similar to the real situation, more advanced and natural human–computer interaction are required. In facts, the 3D visualization with gesture interaction helps the clinician in exploring the data especially in critical medical environment such as in operating room where it can replaces 2D images that commonly used to assist the surgeons to navigate the patient heart. Other problem that arises from the situation is the surgeon needs to browse the scans images without having any physical touch since they cannot leave the sterile field around the patient.

The time duration also need to be considered where the surgeon needs to browse safely during operations where the time is critical in saving the patient lives. Moreover, the amount of time that required for learning the interface need to be considered as well in developing the new solution especially for the clinical uses. Blood flow through the sequence of compartments is subject to changes in direction and luminal diameter, and as a consequence, flow is multidirectional and vortical with a tendency to curl or spin in the cardiac chambers during various phases of the cardiac cycle [3, 4]. The basic idea is how to use medical imaging technique to create a virtual model of the heart wall motion, blood flow dynamics, and mechanical strains. Visual 3D holographic, haptic and sonic interaction with the heart model also can be utilized to get an attractive understanding of the heart function and also for helping the diagnosis process as a complement to medical imaging information. In addition, the interactive interface opens for modifying the virtual heart, simulating cardiac disease or available treatment options, such as choosing between different mechanical heart valves, and finally, it also possible to use as a tool for decision support in planning surgery or other treatment.

5.2 Related Works

Most of the previous researchers have produced interactive ways to visualize and interact with 3D heart model. Previous researcher had proposed a natural interaction on 3D medical image viewer software by combining both hand and body gesture to control mouse cursor [5].

Meanwhile, Kipshagen et al. [6] had demonstrated a touch free input device for controlling the medical viewer. They had used 3D hand position generated from stereo camera that combined with open-source medical viewer and named it as OsiriX DICOM viewer that uses OpenCV library for hand gestures. Wachs et al. [7] in their studies had implemented a real-time hand gesture interface to manipulate objects within medical data visualization environment by using one-handed gesture. They used both dynamic and static navigation gestures and had used haar-like feature to represent the shape of hand. The gesture recognition system was used in sterile medical data-browser environment. Unfortunately, due to lack of training and testing set, there are some user confusion during doing the gesture and had suggested to use both hand to control the gesture rather than only one hand gesture and testing their system with more gesture vocabularies.

Another framework was proposed by Soutschek et al. [8], where gesture-based user-interface had being used for the exploration and navigation through 3-D data sets using a time-of-flight (ToF) camera. In their studies, they had achieved high successfully rates for most of gestures their proposed using ToF camera. For the extension of their work, they had recommended an enhancement by integrating virtual button and hand gesture for selecting the volume of interest and do evaluation in clinical environment.

In cardiac visualization, human gesture also being used to give a real-life situation in diagnosis the heart disease. Ioakemidou et al. [9] had demonstrated a 3D heart visualization with hand gesture and haptic interaction to enhance the understanding of heart function during the simulation. To interact with the heart simulation, they had used open and closed hand as an input to user interface of the system. However, the previous research in medical visualization still not explores finger gesture interaction as an input to the user to interact with virtual heart. Based on this drawback, the author propose a framework that uses finger gestures as an input to interact with the 3D cardiac visualization that can helps enhancing the way human interacting with device especially such critical environment.

The other researcher proposed image guidance for total endoscopic coronary artery bypass (TECAB) by using 2D–3D registration techniques that can deal with non-rigid motion and deformation [10]. The other researcher also involve robot to assist the medical robotics and computer-integrated surgery [11].

5.3 Arm and Finger Gestural Input on 3D Holographic Interactive Heart Simulation

Finger gestural tracking is techniques that being employed to know the consecutive position of the finger and also to represent object in 3D environment. Hence, a framework had being purposed to have capability on tracking the user finger in 3D environment. The user are only allows to use their finger as an input to manipulate the 3D model. The interaction of 3D heart visualization were attached based on the hand finger gestures command that being executed without touching the

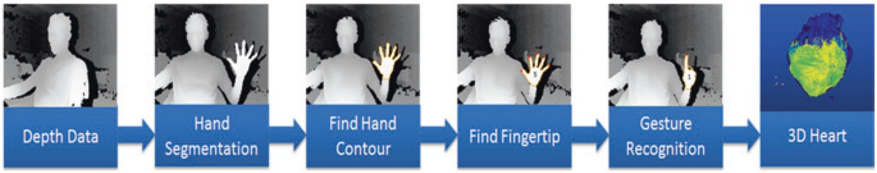

Fig. 5.1 Fingertip identification workflow

display or the viewing screen. Therefore, before the system can recognize the user hand finger gestures that been done, there are several preliminary process that needs to be executed first in order to system work correctly. Figure 5.1 shows the hand finger tracking and gesture recognition of proposed system.

5.3.1 Hand Segmentation

Once hand segmentation process is completed, the system will extract the depth data from the Kinect sensor. After depth data being processed then the segmentation process will be executed. The aims of hand segmentation process is to separate the hands images from background images. It being done by setting a specify depth range where the hand gesture images will recognized. The depth range distance that being set into the system range from 0.5 to 0.8 m which is an optimum distance for the segmentation process. The segmentation process will store the entire depth pixel between the specified ranges to be used for next process.

The next process is to create partition for all pixels and classify it into two groups of hand pixels data by using K-means clustering algorithm. K-means clustering is a method to partition all pixel data into two separate hands that being recognized same as implemented by Li [12]. After the clustering process completed, the next process is to compute the hand contour by using Graham Scan [13] and a modified Moore-neighbour tracing algorithm that used to detect the hand contour as well. All the process being accomplished by using group of hand point that being stored from the previous process.

5.3.2 Fingertip Identification

In order to identify the hand fingertips, there are several process and algorithm that being used in order to identify each fingertip that being used. The first process that need to be done is to scans all the pixels around the user hand by using contour tracing algorithm same as implemented in Li [12] study until the hand contours are detected. After the hand contours are detected, the next process is to detect the centre of the hand which is the user palms that used for normalizing the fingers point direction. Finding the hand palms is important to decide whether the user

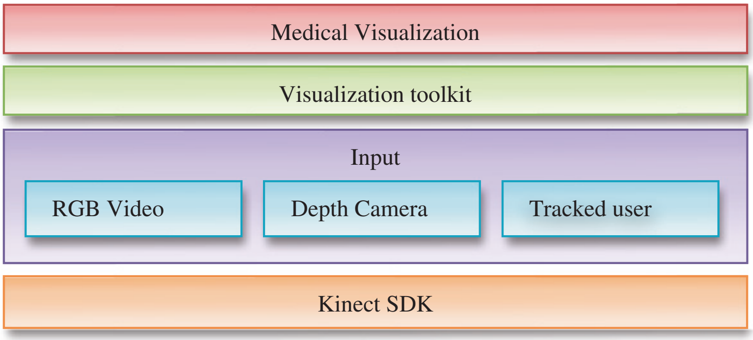

Fig. 5.2 System framework of the application

hand is open or closed states and whether the fingers are bending or not. To detect user fingertips, the three-point alignment algorithm is being used where the data pixel are came from convex hull and hand contour data pixels that came out from the previous process. After successful detects the user hand fingertips, the following process is the gesture recognition where the total number of hand fingertips calculated and being recognized by the Kinect to choose gestures command for interacting with 3D heart visualization.

5.3.3 Gestural Identification

In order to specify gestures that being done by the user, all the previous process must be successful conducted. The gestures that has been developed is unique because it counted by the number of fingertips that recognized by Kinect camera and the system will execute the gesture commands to move or manipulate the 3D heart visualization. Meanwhile, Turk [13] had said that the primary goal of virtual environment (VE) is to provide natural and flexible interaction. Having using gestures as an input modality can help to achieve that goal. He also stated that human gestures are certain natural and flexible. It more efficient and powerful especially compared to with the conventional interaction modes. Although sometimes interaction technologies are overly obtrusive, awkward or constraining, the user experience is ruined and imposes high cognitive load on the user as well. But it can be solved by give complete training to user and introduce more specific and natural gestures so it can helps improve the user cognition to use the system. The proposed system also introduce a new gestures by using hand finger where it's become key activities in designing touch less interface besides having only using hand palm that may higher user cognition to interact to the system. Choosing specific gesture for the interaction, takes both hardware characteristic of the input device and the application domain where the action is executed. The overall system component at 3D holographic interactive heart simulation is portrayed at Fig. 5.2.

Figure 5.2 shows the overview of the system framework with the essential component that support the system. This application is used with the 3D Slicer, an open source medical visualization software which able to load a 3D volumetric medical data. There reasons why 3D slicer is used to be used with the application. Medical area is well known for DICOM (Digital Imaging and Communications in Medicine) data format which is implemented in almost every radiology, cardiology imaging, and radiotherapy device (X-ray, CT, MRI, and ultrasound). 3D Slicer is able to load this data format and visualize it into 3D model. The result of visualized model is depending on the user interest area.

Kinect SDK is the foundation for the application since it provide the information that is required to identify the users hand and arm gesture. This SDK can provide image and users skeleton information obtained from depth camera and RGB camera. There are also microphone array that can be used to acquire audio data. The information that is required in the application is the user skeleton data because it contains the movement information that needs to be processed to identify and recognize the gestures.

Our application also uses the user's skeleton data that is tracked by Kinect and monitors the hand and arm movement. The movement is compared with a set of movement criteria to identify which gestures are done by the user. Each movement has its own criteria that make its unique from other gestures. Some gestures require to use both hands and other only require one hand for the gesture to be recognize. Every gesture has different ways of sending input to the software. Some gesture simulates keyboard input and sends to the software while others need to simulate the mouse movement and click event for the software. Each recognized gesture done by user will simulate the input and these inputs are sent to 3D Slicer depending on the operation assign for the particular gesture.

At the beginning, user needs to setup the Kinect sensor and the medical visualization application so that the visualized model is ready to be used with the application. The interaction flow start with hand and arm gestures from user. Kinect will track the user movement and send the information to the application for the gesture recognition process. Application's output is the input simulated that is used to control the medical visualization. This process is detailed out at Fig. 5.3.

5.3.4 Interaction Flow

See Fig. 5.3.

5.4 Experimental Result of Holographic Visualization and Interaction Control

The proposed system has provide two main interaction which ares arm-hand and finger interaction. The user is allowed to used their hand or arm for far distance control and for closed control they can use finger gesture. Figure 5.4 show the

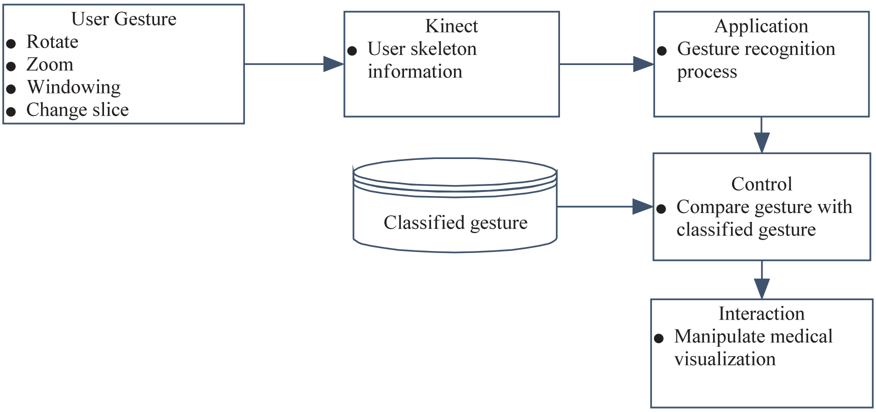

Fig. 5.3 The flow of interaction for hand and arm gesture

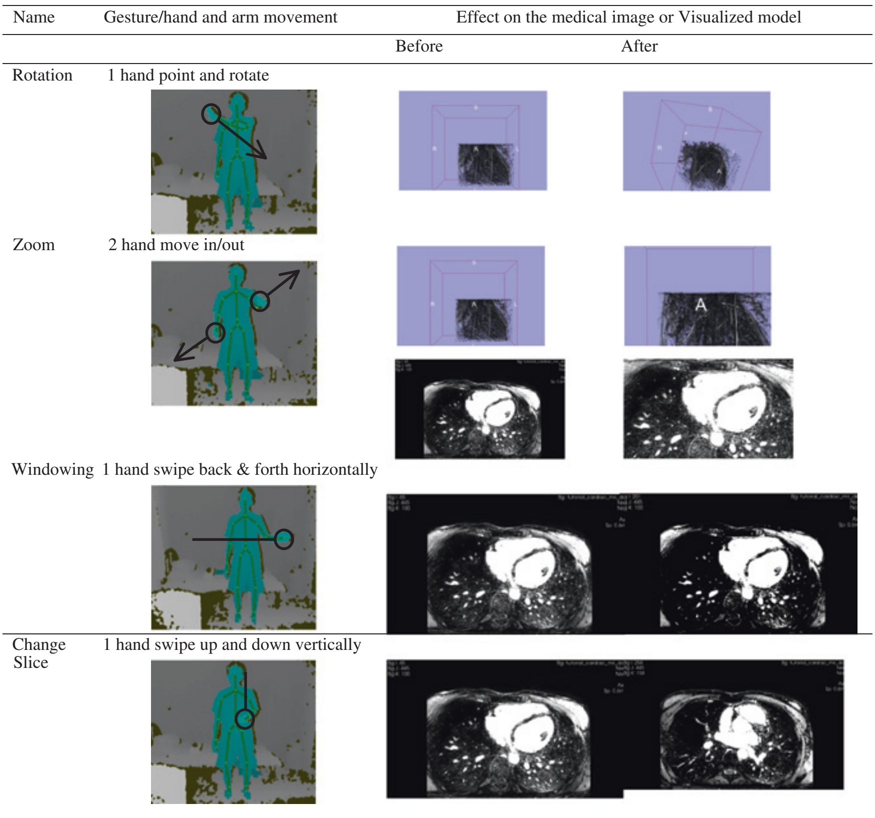

Fig. 5.4 The effect of gesture to the medical image/visualization

Table 5.1 List of full gesture

Name	Gesture/hand and arm movement
Rotation	1 hand point and rotate
Zoom	2 hand move in/out
Windowing	1 hand swipe back and forth horizontally
Change slice	1 hand swipe up and down vertically
Close application	Right hand wave
Reset view	Left hand wave
Change viewing type	1 hand push forward

available gestures in the application used to control and manipulate the medical image and visualization model. Rotation can be done using 1 hand at the front, pointing at the start position and drag to rotate it based on the needs to rotate the visualize model. We can see that action signifies holding and turning the object. The model starts rotating when the user's hand is inside the gesture recognition area. The movement of the arm is computed and the direction of rotation is sent to the mouse as input for rotation process.

Zoom are divided in two types that is zoom in and out. Both gesture are quite the same but different in direction. Zoom out require user to show both hand at a distance and move them closer. Zoom in require user to show both hand at a close distance and move them further from the other. The distance of the hand before and after the movement are used to simulate the input of the mouse scroll. Mouse scroll can be used to adjust the zooming capability of medical visualization. These gesture is signifies that user want to enlarge of shrink an object.

Windowing is the process of selecting some segment of the total pixel value range (the wide dynamic range of the receptors) and then displaying the pixel values within that segment over the full brightness (shades of gray) range from white to black. Windowing process can be done moving one hand back and forth horizontally to set the window size based on the user's need. The gesture is much like controlling slider of a window size.

Medical image contain many slices that can be process and visualize in 3D volumetric model. The medical visualization application allows users to change the image slice so that they can study the image from different position. Changing image slice can be done by swiping one hand in up or down direction to change the image slice. This gesture is only valid to be used on 2D medical image. Table 5.1 show the gesture that provided in the application that can be used in the application. There are also gestures that can be used to do operation that not related in navigate and manipulate the visualization. Each gesture has its own operation to avoid confusion.

This section will explains more details regarding the implementation for each gesture and it effects to the rendered 3D cardiac volumes. Each gesture has its own specification and commands to the cardiac model in the system. There are six gestures that able to be used by user to navigate to the cardiac visualization. Before we described each gesture, this section first will described about the environment details of the project development and then about the result of project.

Fig. 5.5 Drag gesture scenario

5.4.1 Environment Details

The interface has been written using C++ language and had being built on open-source and cross-platform libraries, which had combined and extended to support medical imaging processing and interaction functionalities. In order for Kinect able to generate raw depth image, OpenNI library had been used which is an open-source framework for natural interfaces together with middleware component NITE, which provides a closed-source that being used to communicate with the Kinect device.

The gesture control interface was described in the paper, it was integrated with VTK which open-source visualization toolkit that being developed for visualization uses especially for medical purposes where they need to correct represent and navigate the data at different spatial and temporal scales. Besides that, VTK had being developed allows new module to be added to support computer-aided medicine application together with the gesture interaction to 3D visualization of cardiac data. In order to test functionality of system work accordingly, the project was divided into several type of scenario which based on hand finger gesture that being specific into the system to interact with volumetric data.

5.4.2 Scenario A

For the first scenario as shown in Fig. 5.5, the finger gesture that being used is drag gesture. The drag gesture allows the user to drag the model from the initial position to a new position. In the order to allow the users to move the model, only one finger needed do the process. The cursor or the point of user hand needed to touch the surface of the model to move it. To drag the model, the hand of the user must be at valid distance that already being set to 5–800 mm. At this distance, the system can recognize the user hand gesture.

5.4.3 Scenario B

The second scenario, gesture that introduced is zoom-in and zoom-out gesture. For zoom gesture, it allows the physician or research to look more detail inside the 3D cardiac model. Not only that, it also helps the give better understanding about the

Fig. 5.6 Zoom gesture scenario

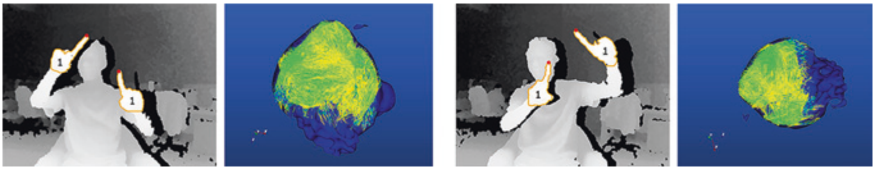

Fig. 5.7 Rotate gesture scenario

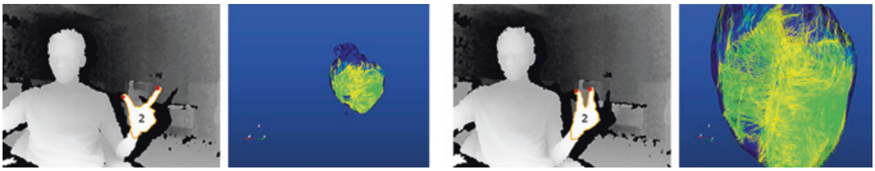

Fig. 5.8 Spread and pinch gesture scenario

patient heart. In order to use gesture, the users must use one finger from each hand to able the cardiac model to be zoom. The zoom-in and zoom-out also allows the researcher to analyse the symptom inside the patient heart where they able to see the detail of cell inside of heart, as shown in Fig. 5.6.

5.4.4 Scenario C

Figure 5.7 is rotate gesture. The rotate gesture will helps the researchers to see the part that not see in view where by rotating it, the researcher can the hidden part of the 3D model. To use this type of gesture, the researcher also need to use finger from each hand and then rotates it to up and down (Fig. 5.8).

5.4.5 Scenario D

The last gesture is spread and pinch gesture where it same capability same as the zoom gesture. The different from zoom gesture, it’s only required the user to only use two fingers from a hand. Besides that, for spread and pinch gesture the zoom

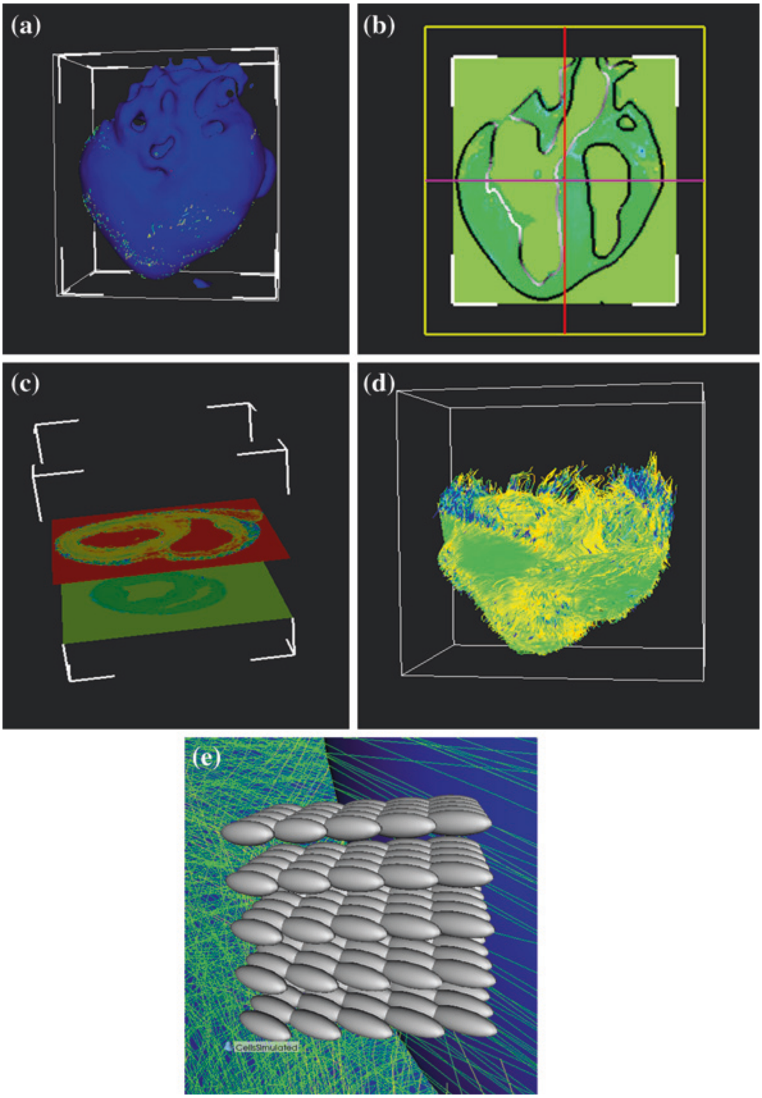

Fig. 5.9 **a** Is the view of the whole heart while **b** and **c** is segmented heart for different view of heart with segmented region. **d** Is the mainstream of blood flow and **e** shows cardiac cells

scale that being done are in small scale different from zoom-in and zoom-out gesture. By using this features, researchers will able to manipulate the cardiac model because it give more insight about the patient heart so it will helps to prevent the spreading of the unwanted virus by touching any physical device when the surgeon in operation room sterilized. Furthermore, the use camera sensor like Microsoft Kinect also does not requires special lighting condition where as we know in the surgery room the lighting condition are swallow and only focusing on the patient.

Several screenshot of our heart visualization with different stages are displayed in Fig. 5.9.

Fig. 5.10 Zspace device. *Image* from http://zspace.com/wp-content/uploads/2012/12/zspace-medical-app-crop675x487.png

The holographics device that will be used in this system is Zspace from zSpace, Inc. Our system still early implemented and merged with Zspace device, because previously the proposed system is already integrated with multi display such as HMD and 3D tv, As illustrated in Fig. 5.10.

5.5 Conclusion

The user is allowed to interact with the medical image and 3D visualized model using a touch-less based interaction technique. This method is done by recognizing the gestures shown by the user. Application is developed to recognize the gestures and simulate inputs corresponding to gestures. Each gesture has its own operation on the medical image or 3D volumetric visualization. The new proposed system had being developed that uses non-touch based gestures for semi-immersive 3D virtual medical environment. The sensor camera technology was used to enable gesture that had specifically design and developed by considering the user skill and needs of the clinician when doing diagnosis where they need to interact with 3D virtual heart in order to detect symptoms of the disease. As mentioned early, the aims of this chapter is to enhance the performance and to give new interaction way to daily clinician tasks by giving them to manipulate and examine the three-dimensional heart that reconstructed from the scan data by using hand finger gesture. It is also a strong belief the medical experts especially the cardiologist can obtain great advantages by the virtual technologies where it easy their works by providing them with natural and intuitive manner to interact in 3D space not only by using their hand but only also their fingers. Lastly, we also conducted a formal usability evaluation of the proposed solution that involved the user. By doing that, the data that we collects will be further analysis to validate the proposed finger gesture and to get better understanding of usability issues that not yet being recognized. For the future works, we are planning to add more finger gestures to interact with volumetric data. Finally, in order to provide a usable tool for computer-assisted education and trainings for clinicians, a semi-immersive multi-user interaction approach can be proposed where the system can detect more than one user.

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Chapter 6
Designing Simulations for Health Managers in Sub-Saharan African Countries: Adherence to ehealth Services

Miia Parnaudeau and Hervé Garcia

Abstract The aim of this work is to study the way health managers may adopt ehealth services, in Sub-Saharan African (SSA) countries. Sub-Saharan Africa accounts for 11 % of the world's population, yet bears 24 % of the global disease burden, and commands less than one percent of global health expenditures. In such a critical situation, questions of health management, efficiency and performance take another dimension. Designing specific ehealth services for SSA countries implies consequently to have precise understandings of the challenges faced by health actors, of health practices existing in those environments, but also of actors' adherence to IT tools. Accordingly, we have created a serious game, especially intended to health managers. Managers' adherence to ehealth services is measured on the basis of four indicators: governance practices and adherence to partnerships, adherence to ehealth services, and country's given critical situation.

Acronyms

SSA	Sub-Saharan Africa
ESA	European Space Agency
NGO	Non-Governmental Organization
WHO	World Health Organization
GDP	Gross Domestic Product
GNP	Gross National Product

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Intelligent Systems Reference Library 68, DOI: 10.1007/978-3-642-54816-1_6,

WHS World Health Survey
PPP Public Private Partnerships
HDI Human Development Index
NCD Non Communicable Diseases

6.1 Health Practices and eHealth services' Adoption in Question

If health financing impacts directly on practices and performances in those countries, using telemedicine is more than a question of resistance to change.

Accordingly, the aim pursued in this section is firstly to discuss the most adapted manner to characterize SSA countries health systems. Indeed, identifying properly the challenges faced by health actors in their environments is an issue of primary importance. The design of a simulation intended especially to health managers must refer to real situations. In doing so, managers' adherence to specific ehealth services will be properly captured.

In the published literature dealing with SSA health systems, traditional divergences between private and public institutions constitute an important concern. As a consequence, *the primary source of health financing is generally seen as the key matter*. Besides, the WHO recommends a minimum of 34–40 USD per capita to provide the essential package of health services (Ouagadougou declaration on Health Financing, African Region Member States, 2008).

Two categories of countries have been distinguished: the poorest countries that have low means to allocate in their health systems, and countries where a political choice implies very low expenses to health. A first interesting result obtained is that the poorest countries in SSA are not the ones that allocate the lowest amounts to health. Zimbabwe is the poorest country but allocates more to health than Congo, which ranks among the richest countries of SSA. This statistical information offers however an incomplete picture of the heterogeneity of SSA countries. It is the reason why we aim at finding common factors between health financing systems, relying on specific data analysis methods.

These calculations helped us to identify three homogeneous groups of countries: *public oriented financing countries, private oriented financing countries, and mixed financing countries*. Two main factors have then been extracted: *public versus private financing modes and international versus national support to health*.

In those interpretations, GDP Per Capita no longer stays of primary importance to describe the current situation in health systems. It is rather the *Human development index,* which integrates notions of education and health. It is a good candidate to illustrate health policies' outcomes. The statistical results obtained showed indeed that specific financing modes could be significantly associated to human development thresholds. More precisely, public and mixed financing modes were strongly associated to high levels of Human development, whereas private

Table 6.1 Top ten critical countries

Rank	Less than 1,227 USD (GDP per capita)	Less than 4.8 % of GDP allocated to health
1	Zimbabwe (256.08)	Congo (2.5)
2	Burundi (372.86)	Eritrea (2.7)
3	Democratic Republic of the Congo (413.98)	Angola (2.9)
4	Liberia (552.34)	Seychelles (3.4)
5	Eritrea (656.99)	Gabon (3.5)
6	Niger (690.88)	Madagascar (3.8)
7	Central African Republic (741.48)	Central African Republic (4)
8	Malawi (869.89)	Benin (4.1)
9	Sierra Leone (878.67)	Cape Verde (4.1)
10	Madagascar (916.01)	Mauritania (4.4)
11	Rwanda (922.21)	Chad (4.5)
12	Togo (927.50)	Comoros (4.5)
13	Ethiopia (1,074.47)	Equatorial Guinea (4.5)
14	Mozambique (1,127.35)	Kenya (4.8)

Missing countries are (no statistical information available): Somalia, Sudan, Tanzania and Zimbabwe only for total expenditures to health in % of GDP. *Data source* WHO (2010)

financing modes and international support were associated to low levels of human development. Plethora of donors in some SSA countries weakens health systems. Successful models seem rather to rely on coordinated structures.

These results have key consequences on the way the scenario of the simulation will be constructed. They are offering precious information about how rules, physical and material conditions, but also how attributes of the community affect the structure of action arenas. It offers the opportunity to describe the incentives that individuals face, and the resulting outcomes.

6.1.1 Health Financing Impacts Governance in SSA

The distribution of GDP per capita and the amounts of GDP allocated to health in SSA countries are very heterogeneous. The countries identified in the first column of Table 6.1 are the poorest ones. Zimbabwe ranks first with the lowest GDP per Capita in SSA in 2010. In this group of 14 countries, GDP per capita is less than 1,127 USD. In the second column, SSA countries that allocate the lowest amounts of their GDP to health are ranked. Congo is the country where expenditures to health are the weakest in 2010.

Some countries ranking in the second column are not in the first one. The case of Seychelles is particular: with a GDP per capita of 27,222 USD, this country allocates 'only' 3.4 % to health. Households' expenditures stay low (5.4 %), as external resources (4.2 %). Kenya finds itself in the same situation, even if it is not for the same reason. External resources and households' efforts constitute a strong part of health financing. Statistical data may give sometimes distorted pictures of

Table 6.2 Health expenditures profiles

Group 1	Group 2	Group 3
Essentially private financing modes	Mix	Essentially public financing modes
Sierra Leone	Mauritius	Madagascar
Guinea-Bissau	Togo	Ghana
Guinea	Congo	Djibouti
Côte d'Ivoire	Mali	Comoros
Chad	Burundi	Zambia
Uganda	Kenya	Namibia
Cameroon	Eritrea	Swaziland
Central African Republic	Dem. R. of the Congo	Malawi
Nigeria	Benin	Equatorial Guinea
Sao Tome and Principe	Gabon	Cape Verde
	Mauritania	Angola
	Niger	Mozambique
	Burkina Faso	Botswana
	South Africa	Lesotho
	Ethiopia	Seychelles
	Rwanda	
	Senegal	
	Gambia	

Pearson correlations—Thresholds higher than 60 % for each group of countries. *Data source* WHO (2010)

African realities. In many works published on this question, an emphasis is made on two distinct categories of countries:

- The poorest in SSA;
- The ones that allocates the lowest amounts of their GDP to health.

The same methodology was retained. The underlying aim here is in fact to identify countries facing high difficulties in financing their health needs, and the ones that deliberately choose to allocate low amounts of their GDP to health.

If some countries cannot pay for their health needs, for others, it is a political choice. And, for countries like Kenya, it's not only a political choice: international support is high. At this stage of the analysis, there is consequently a need to look *after common factors between SSA countries: can similar health profiles be drafted?*

In Table 6.2, measures of correlations between countries helped to identify three groups. In the first one, private expenditures were the highest. In the last one, public expenditures on health were the highest.

In between private and public oriented financing modes, a group can be distinguished. These countries are characterized by balanced levels of health expenditures: private and public expenditures to health are almost equal. As a consequence, this cluster can be defined as a group where financing modes constitute a 'Mix'.

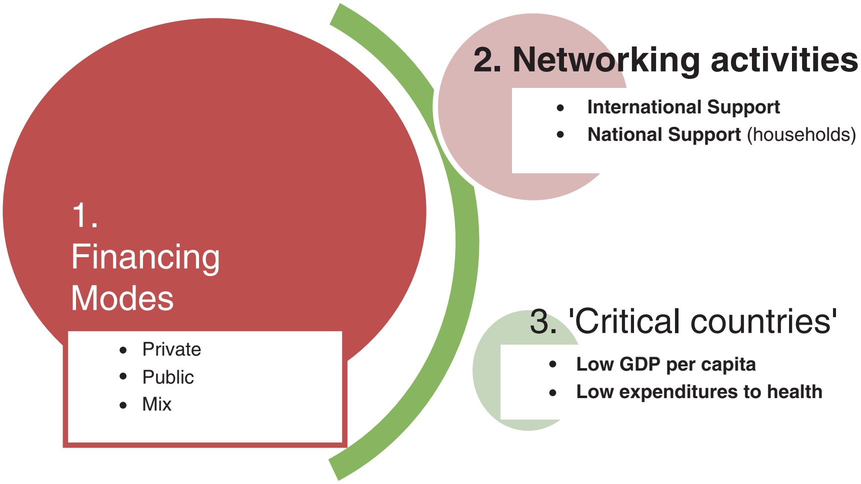

Fig. 6.1 A possible classification for SSA countries health systems

Developing appropriate services for eHealth to respond to the challenges that SSA countries are facing requires a better understanding of their existing health systems. Although there is an undoubted acceptance on the importance of eHealth in all these countries, its extent, forms and related practices may vary across countries because of different or very different situations. At the moment, a systematic classification of health profiles in SSA is lacking. It is, however, compulsory to allow for relevant comparisons and avoid misleading generalizations.

All the information collected on health care spending data (WHO 2009 and 2010) in SSA countries have been reorganized so as to extract the most interesting (and significant) oppositions and similarities. The data reduction method[1] we used highlighted the existence of very specific country profiles. These profiles are characterized by three kinds of indicators (in order of importance): financing modes, networking activities, and countries' situation.

Such an operational form (Fig. 6.1) for data gathering and analysis relies essentially on scientific criteria. In SSA, statistical information is sometimes considered to poorly represent the realities. In an interesting paper, Xu and al. [17] discussed this issue in focusing their work on household expenditure and health expenditure data.

In comparing 50 surveys provided by the World Health Survey to 37 other studies (namely the Living Standard Measurement Survey, Household Budget Survey and Income and Expenditure Survey), they showed that information within the surveys was fairly similar. If the WHS was found to report lower total household expenditure and higher out of pocket expenditure, the data studied was not considerably different.

[1] Detailed calculations are available on request. The database can be found on WHO website, for the years 2009 and 2010.

As a consequence, this proposition must be seen as a first attempt, on the basis of the information available on referenced websites, such as the World Health Organization.

More efforts to standardize the questions in collecting expenditure data in surveys are needed. Better data collections are needed too. These issues are already largely recognized, even if it is still a work in progress.

6.1.2 More than Resistance to Change Issues

The data analysis realized in the previous section approached only partially the question of SSA countries' health governance. If some common characteristics have been extracted, and if some specific profiles have been drafted, the nature of the governance models in use remains very vague. As we are working with 48 countries, but also with an important number of observations (health care spending data, Gross Domestic Product per capita, Human development index), this is quite normal. However, *the in-depth study of the groups extracted* (Table 6.2.) showed that ehealth services' use *is more than a question of resistance to change in SSA*.

In order to understand how much the adherence to ehealth services may be influenced by the practices in play in these countries, some examples can be given.

Malawi is one of these interesting examples. Even if health expenditures are, in this country, essentially stemming from *public sources*, there are also important amounts *of international support* to take into account. With a Gross National Product per capita of roughly 160 USD in 2004, Malawi ranked among the world's five poorest countries, and has one of the lowest life expectancies worldwide due primarily to HIV/AIDS, dropping to just 37 in 1996, and back to 43 in 2000 [15]. As a consequence, Malawi became a primary target for international support. It would be easy to believe that this country is a good candidate for the use of IT technologies. In fact, it is just the opposite. The high level of international support renders the identification of functioning modes difficult. The existence of a plethora of donors weakens health system's coordination, and characterizing funding modes in such situations is almost impossible. The adoption of ehealth tools at a national level may therefore be difficult.

In *Liberia*, 55, 1 % of health financing comes from *international support*. The rest (44.9 %) is divided between public and *private funds*, but is essentially private. Liberia has gone through civil crisis for over a decade, which has resulted in the destruction of infrastructure and disruption of basic services delivery, particularly in Monrovia, the capital city. In 2006, most of the people living in Monrovia were without adequate environmental sanitation and waste management services. Such a situation posed a serious health risk to the residents [7]. Liberia experienced 14 years of protracted civil conflict (December 1989 to August 2003) when the United Nations Mission assumed peacekeeping duties. These years of conflicts resulted in over 200,000 deaths, the displacement of approximately two million people, the injury and traumatization of countless others, and the virtual destruction of Liberia's infrastructure and economy [13]. In such a critical situation, even if there's a pressing need for ehealth services, their adoption may well not be of prior concern.

In countries were some *public–private partnerships* (PPP) for health has been developed, the situation is quite different. The efforts required to manage the complex relationships that underlies such partnerships may constitute a valuable experience and adherence to ehealth services may well be facilitated.

While there is recognition about the role of PPPs in addressing global health issues,[2] researchers have emphasized that public and private organizations have significantly different goals, values and processes. According to Ramiah and Reich [9], partnerships are therefore advised to invest in extensive planning and learning, and then start a process of incremental engagement, beginning with arms-length philanthropic involvement and moving carefully towards highly collaborative models, which involve intensive and regular communication between partners, the exchange of multiple resources, and engagement at various levels of partner organizations [1, 2, 11].

In an interesting paper published in 2003, Otiso [8] showed that such efforts exist. In *Kenya*, and more precisely in *Nairobi City*, tri-sector partnerships involving the state, voluntary, and private sectors constituted a promising way of addressing the issues: while difficult to initiate and maintain, such partnerships have unique and mutually reinforcing strengths that could enable participants to increase effectiveness.

PPPs might be seen as complementary to public services. In 2010 in South Africa, the National Department of Health called on the private sector to assist in clearing the infrastructure backlog at state health facilities based on their good track record in delivering large projects for the soccer World Cup.

The private sector was subsequently contracted in public–private partnership agreements to help revamp the biggest tertiary hospitals in South Africa, being Chris Hani Baragwanath in Soweto, George Mukhari in Ga-Rankuwa, King Edward VIII in Durban, Nelson Mandela in Mthatha, and Limpopo Academic in Polokwane. In the proposed hospital partnerships, the private sector is to raise loans to fund infrastructure upgrades and to maintain equipment and facilities for as long as 20 years.

Our statistical analysis confirmed these assumptions. Funding modes (public, private or mixed) can be significantly associated to human development in SSA countries. Choosing a specific governance model will have consequences in terms of performance. The results obtained showed that public funding modes, but also mixed funding modes are associated to high levels of development. Private funding and international support are associated to weak levels of human development. SSA countries' adoption of ehealth services is inevitably influenced by such governance practices. Tests[3] are confirming this association between health funding

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[2] See Reich [10] and Widdus [16].

[3] Chi-square tests of association. Calculations available on request.

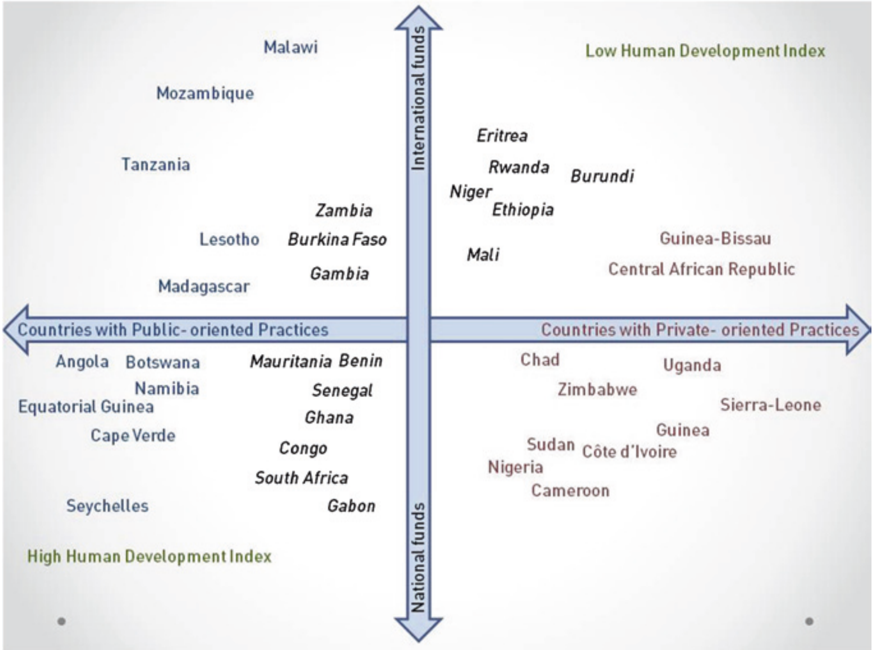

Fig. 6.2 SSA countries health profile: a summary

and performance: there is a statistical association between high levels of HDI and public/mix funding, whereas low levels of HDI are associated to high levels of international support and private funding (Fig. 6.2).

6.2 A Game Scenario Constructed as an Experimental Tool for Research

Numerous articles point the effectiveness of serious games for acquiring decision making skills in management [3–5, 12]. The purpose of this work is not to discuss questions of knowledge transfer or metrics of the effectiveness of such learning tools. The aim is rather to give *a detailed presentation of the scenario* drafted on the basis of the contextual analysis provided in the previous section. The conceptual modeling of our serious game followed the methodology proposed by van der Zee et al. [14]. Accordingly, the work has been organized in 5 steps: understanding the learning environment, determining objectives, identifying the model's inputs and outputs, and determining the model's scope and level of detail.

The exploration of the *learning environment* was made notably through different feedbacks collected from the NGOs involved in eLearning programs in SSA and engaged in the eHSA consortium. AMREF (http://www.amrefuk.org/) trains thousands of health workers from across Africa every year. MERLIN (http://www.merlin.org.uk/) help communities set up medical services for the long term including hospitals, clinics, surgeries and training for nurses and other health workers. In Africa, eLearning creates accessible opportunities for continuing education and expert advice, as many communities are isolated.

A first prototype of this game has been prepared for an event organized in Nairobi, Kenya, in November 2012, in AMREF's training center. This serious game was introduced as a tool intended to contribute to health actors' awareness and insights on the way managerial decisions influence behaviors and health performance. In turn, the simulation was meant to facilitate health managers in showing their skills in making balanced and founded decisions.

If one of its first tasks was *to communicate to health managers* on ehealth services and good governance practices, the simulation was also supposed to capture health manager's adherence to ehealth services and IT tools. In that sense, it can be seen as an *experimental tool for research.*

During the game, the health manager is supposed to face a burden of disease. All his decisions are registered, so that a complete profile can be generated at the end of the game. Managers' adherence to ehealth services is measured on the basis of four indicators: governance practices and adherence to partnerships, explicit adherence to ehealth services, and country's given critical situation.

The players will have to identify success criteria. These criteria are, according to our previous section, the following:

- Policy making: efficiency of reforms and equity
- Funding mobilization: public/private expenditures, long-term predictability of international aid, balance between costs needs and financial support …
- Resource creation: incentives for the health workforce, knowledge and operational skills support…
- Services delivery: quality, payment, maintenance and surveillance…
- Outputs produced: Utilization of health services, reduced costs…

The game stops with *a detailed debriefing.*[4] A spreadsheet gathering the player's points at each steps of the game is also automatically generated, for experimental research. The software used to create this serious game is ITyStudio.[5]

6.2.1 Pre-simulation Original Objectives

Knowing players' places of origin and the staff appointment they hold will help us to determine in which configuration is their health system (private, public or mixed oriented practices). However, there is also a need to collect more

[4] For detailed discussions concerning debriefing, see Crookall [6].

[5] http://itystudio.com/en/

information on the challenge they face on a daily basis. This is why we have firstly created *a questionnaire*.

As we can see (Table 6.3), a number of different health care services have been tested: eCare, eLearning, eSurveillance, health asset mapping, financial management, human resources management, performance management, supply chain management and ICT management.

The question that health managers were asked was to assess their interest in those different services, within an explicit list. This list was integrated in our serious game's scenario. While playing, the interest shown by the player helps bring about a better understanding of managerial choices. This will usefully contribute to seizing concrete opportunities for co-operation. But it also provides us the opportunity to relate countries' health profiles to the actual practices applied.

The serious game is intended to capture information on the diversity of national situations and options. The data entry is although different: it is rather the player's behavior during the simulation and the strategies chosen that are observed. As a consequence, the governance practices in play are revealed.

Once the results are known, we can begin to look if our initial assumptions are confirmed. Is the *health systems*' *division* proposed in the first part of this work properly illustrating the realities experienced by health managers in SSA?

The answers obtained with the survey confirmed the value of doing such a division, but we expect a lot more of the serious game. The results collected at the end of the simulations will lead to a further push in this direction. Indeed, *the best candidates to adopt ehealth services*, but also *health management operating modes* will be accurately observed.

6.2.2 Decision Tree and Game Mechanics

The game starts with a *burden of disease*. In this context, the player is required to define more precisely the kind of emergency he had recently to deal with. After watching and discussing all the options in a scene, the player is given the opportunity to make a choice about which option he thinks is best, or depicts the most desirable provider behavior for that particular situation.

The way these different scenes are organized within the serious game can be illustrated by a *decision tree*. In Fig. 6.3, four possible scenes available at the start of play are presented. In Fig. 6.4, the gaming environment is pictured.

Off the options available, there is a rise in non-communicable diseases (NCD). It is a medical condition or disease which by definition is non-infectious and non-transmissible among people. NCDs may be chronic diseases of long duration and slow progression, or they may result in more rapid death such as some types of sudden stroke. Another possible scene is a situation with epidemic infectious disease (any infectious disease that develops and spreads rapidly). The final possibility is a critical situation (war, large-scale starvation, natural disaster…).

Table 6.3 ehsa ehealth service questionnaire

Categories	Services: *level of interest from 1 (not interested) to 5 (very interested)*
eCare	Patient identification, registration and medical file management—Appointment booking—Consultations—Patient's test result—Off line—On line—Send dispensing record—Checking of prescription—Patient satisfaction survey—Update of programs registers—Patient preventative educational care and disease management—Psychosocial support
eLearning	Degree and skills training programmes for community health workers—Health workers social networking around practices—Degree and skills continuous training programmes for medical workforce and administrative staff—Skills training programme for practitioners—Remote access to high quality health information—Scientific database
eSurveillance	Mobile capture and notification of tracked events from e-records—Early warning systems—Real-time epidemiological analysis and threshold alert—Alert and response tracking system—District morbidity and facility mortality notification—Facility mortality regular reporting—Public health and disease reporting
Health asset mapping	District population data bases—Health centre asset registration—Case study and good practices data base—What if scenario development—Budget planning—Partners asset mapping—Health centre and partners connection management—District health assets inventory
Financial management	Services pricing and invoicing management—Mobile payment—Cashier management—Billing and accounting interface with accounting software—Interface with aide health projects settlement—Interface with national health budget, with insurance, with money transfer
Human resources management	Facility hired staff contract and pay management—Facility public service staff management—Facility payroll—Interface with facility accounts and eMoney—Human resources skills and degree management
Performance management	Facility activity reporting based on department erecords or manual—Facility process KPI management—Facility activity and resource use reporting—District process KPI consolidation and management
Supply chain management	Stock management, priority to pharmaceuticals—Reporting on stock level and expiry—Automated warning—Shared stock management—Central purchasing
ICT infrastructure management	Provisioning ICT infrastructure (VSAT, Wi-Fi, Devices)—safe power supply—Broadband communications—Initial training and online training—User forum—Helpdesk—Maintenance of ICT infrastructure—Services catalogue and level management—Internet access

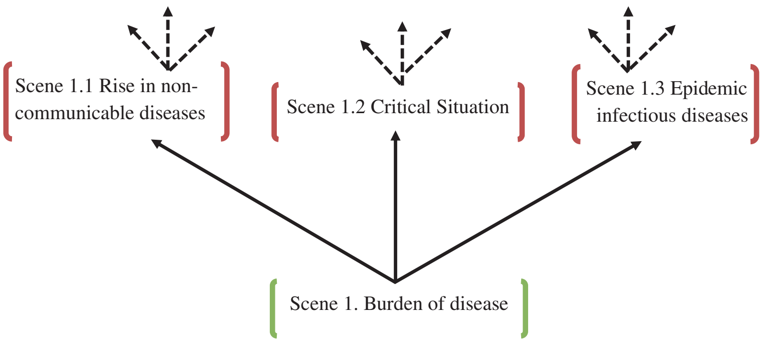

Fig. 6.3 Decision tree

Fig. 6.4 The simulation environment—scene 1

We have chosen to address the issue of *health crisis management* in a virtual environment that has been disconnected from the really difficult circumstances generally experienced. The aim is not to place the player under stress. It is rather to put him in a comfortable situation for thinking about the appropriate strategies to be taken. As a consequence, the speed with which the player will answer or get to the endgame is not evaluated.

Table 6.4 A three-step game

Steps	Aim	Strategies/situations chosen (one scene per each)
1	Describing the situation	Burden of disease
		Rise in non-communicable diseases
		Critical situation
		Epidemic infectious diseases (etc.)
		Situational analysis OK/NO
		Published national medicine policy
		National health workforce OK/NO
		Published list of essential medicines
		Urgent need for health care reform/no urgent need
		Timely health surveillance system
		No timely response to disease outbreaks
		Average availability of medicines OK/NO
		Public per capita expenses OK/NO
2	Solutions already provided and new needs	Protecting the poor
		Managerial practices
		Access to information
		Health care utilization
		Balance between primary and tertiary care
		Interagency intelligence
		Strategic planning (etc.)
		National health plan with PPP
		Uncoordinated number of donors/NGOs
		Coordinated number of donors/NGOs
		National health plan for the public sector
		Social insurance
3	Arbitrages between revenue and optimized supply chain management	Coordinate price structures
		Economize resource inputs
		Common platforms
		Project co-financing
		Extend coverage and quality of services
		Professional ethics instead of profits
		Implementation process
		Seeking for coherence
4	Debriefing	Governance practices
		Adherence to partnerships
		Adherence to ehealth services
		Country's given critical situation

Table 6.4 provides a list for the main stages of the game. This echoes the views expressed by our interviewees and the NGOs in the field. The game's structure was conceived in three steps. Phase 1 is an initial review to identify those *diversities* that manifestly provide relevant basis for the understanding of management operating modes in SSA countries.

A situational analysis helps for example the health manager to better understand the cultural beliefs, concerns, and needs of a community with regards to early developments of his institution (before he begins to implement any kind of solution). It helps to build mutual trust and understanding between staff and community members. The health managers acting without situational analysis are likely to experience higher difficulties. Interesting e-solutions can be rapidly provided in this field, and the serious game is a chance to discover them.

The player may not be aware of situational analysis' usefulness. During the simulation, he can still declare an interest for it, and for associated ehealth services. The player may also be very well acquainted with the subject. In any cases, we are getting into a more detailed analysis of stakeholders' behavior. That is useful in many respects: firstly in terms of communication, as it allows us to present some of our ehealth services. But it is also an opportunity for experimentation, as the player's behavior is accurately observed.

In its second phase, the game focuses on the *solutions already provided* by the health manager. It is also an opportunity for the manager to express new needs, hopefully to be associated with specific e-health services.

Within the broad range of solutions suggested during the simulation, there is the need for a balance between primary and tertiary care. This specific scene offers the opportunity to see how much the governance practices in play in the country may affect the health manager in establishing his strategic plan. In countries where public-oriented practices may prevail, strong concerns will be devoted to health care coverage. In countries where international support is very high, medical care is sometimes very specialized (as donors may ask for special health care missions).

Primary health care strategies include needs based planning and decentralized management, education, inter-sectoral cooperation, multi-disciplinary health workers, and a balance between health promotion, disease prevention and treatment. On the other side, *tertiary care* is defined as a highly specialized medical care, usually over an extended period of time that involves advanced and complex procedures and treatments.

Thus, we can confront the question that was mentioned at the beginning of this chapter. How does general practice fit with primary health care? If health financing impacts governance in SSA, will this be discernible at an individual level? In other words, as regards to players' places of origin, will the balance between primary and tertiary care be different, and why?

Underlying all the scenes available in the second phase of this simulation is a fundamental concern about finding *best practices of governance*. As we noted above, only mixed practices were associated to high level of development. The real issue is then to know if health managers are focusing on human development index or on other types of performance indicators.

During phase three, a very *hands-on approach* has been chosen. Throughout his ongoing management activity, our stakeholder will have had to compromise. This period in the game offers an opportunity to capture the kind of arbitrages that was implemented. Prices structures, resources inputs, common platforms, co-financing solutions…

Table 6.5 A two-step debriefing—evaluated skill: governance practices

Points	Step 1: Diagnosis	Step 2: Solutions/advices
[0–50 %]	Managerial practices are in question in your country. It seems that identifying and applying good practices of governance is difficult Finding the right arbitrage between health coverage and profitability is tricky. Uncoordinated donors, and multiple health plans may also considerably complicate the management (etc.)	Goods practices of governance may be: • Coordinated price structure • Coverage and quality of services • Strategic planning • Balance between primary and tertiary care • *Harmonized procedures in management*…(etc.)
[50–100 %]	Your adherence to collaborative governance models is high. Is it because you have already experienced successful projects? (etc.)	

Game ends with a proposition for debriefing. The debriefing summarizes in 4 axes the players' statistics and abilities. Each axis is allocated with one graduate scale in percentage (0–100 %).

6.2.3 Debriefing

In Table 6.5, *the proficiency testing of health managers* is detailed. The evaluated skill is governance. During the game, the player was supposed to identify success criteria. In choosing one strategy other another during the three phases of the game, he has accumulated points. Once finished, if the total score of points is comprised between 0 and 50 %, the feedback focuses on the reasons for this less than ideal performance.

This feedback is broken down into two areas: *diagnosis and advices*. The diagnosis area is a pivotal element, as it highlights player's profile and working environment in crisis situation. The grading supplied here is very general in scope. A more detailed overall assessment is carried out at the same time in a spreadsheet for experimental purpose. As previously said, the serious game was firstly intended to communicate to health managers on ehealth services and good governance practices. But it was also supposed to capture health manager's behavior and adherence to ehealth services.

The second part of the debriefing aims at giving some advices. For instance, heightening player's awareness of the need for harmonized procedures in management is important. All along the simulation, the player can have discovered cases where providing a centralized process improved the organization of global efforts and maximized health utilization. This can help to build momentum and influence positively its future decision making process.

The debriefing in part 2 is also useful in bringing the player up-to-date with health crisis management developments as well as informing and explaining to him the overall mission conclusions, which also represent the conclusions of his own hard work.

The fact remains that this serious game exists in prototype now. It should be enhanced in a number of areas, including deeper assessment for the debriefing, and additional scenes in phases 2 and 3. The early results are however encouraging.

The operation and evaluation of our experimental research involves the study of 48 countries in SSA. To this end a series of new actions must be proposed to facilitate a smoother roll-out from research and piloting into wider deployment.

Besides the problem of studying these 48 countries, there are a variety of actors representing different agencies and sectors in every health system. The high number of countries to study is not the only difficulty with which to compose. From one country to another, the players involved in health governance processes are different. The observation of specific work practices in health requires a longer time frame, and more resources.

Although some similar characteristics between countries already exist, it is critical to get even closer to health managers in SSA: a constructive basis of practical experiences is needed.

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Chapter 7
Using Visualisation for Disruptive Innovation in Healthcare

Daniel Steenstra and John Ahmet Erkoyuncu

Abstract The chapter provides a view of alternative visualisation technologies to support sustainable healthcare. It presents the developments in healthcare to explain the need for disruptive innovation. The chapter then presents the elements of disruptive innovation (DI) in healthcare to explain the need to co-design solutions with all stakeholders. This is followed by a discussion of the implications and opportunities for visualisation technologies to enable co-designing of disruptive healthcare processes and products.

7.1 Introduction

The current model of healthcare relies on diagnostics, therapy and care being delivered in hospitals using costly and complex technologies. Clinicians need to develop a high level of technical skills and patients are taken out of their community environment. This is no longer sustainable.

Disruptive innovation (DI) can shift healthcare to the community as it offers affordable solutions that are simpler to use. DI consists of three elements: simplifying technology; business model and value network. These have to be developed concurrently involving all stakeholders. This requires co-designing and a whole system approach. Visualisation-based technologies support DI by facilitating the modelling of complex systems and allowing all stakeholders to interact with alternatives.

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The literature review presents developments and applications of visualisation technologies. Research using GE Healthcare's Vscan shows alternative pathways combined with cost/benefit analysis and decision-support systems. This demonstrates the need for visualisation technologies and leads to a discussion on what technologies are required, how these should be developed and validated.

The conclusion highlights the importance of DI for sustainable healthcare and that visualisation technologies are required to enable DI.

7.2 Innovating Healthcare

7.2.1 Healthcare Challenges

Governments and policy makers are faced with an almost impossible challenge of having to provide more healthcare, and of better quality, with limited financial resources. This has been exacerbated by the 2008 economic crisis, which led to many countries having to revise their healthcare policies.

A report of the King's Fund predicts that many countries will have to double their expenditure on health and social care in the next 50 year [1]. The report explores a range of factors that contribute to this increased spending such as "demographics; patient behaviours; treatment practices, technology and health care system organisation". Healthcare technologies are a significant factor; contributing between 30 and 50 % to overall spending.

The increase in healthcare spending obviously has consequences for levels of taxation required but will also lead to reforms of healthcare systems in order to increase effectiveness.

7.2.2 Healthcare Reforms

The increasing demand for healthcare and the economic constraints mean that that simply cutting costs or increasing efficiency will not suffice. Healthcare providers need to become much more effective, which means focusing on prevention, early diagnosis and delivering care in the community.

The UK finds itself in a leading position when it comes to large scale health system reforms with developments closely monitored by other countries. The UK government is responsible for the National Health Service (NHS), which with 1.4 million employees it is the largest health provider in the world. In order to deal with the consequences of the economic situation it quickly put in place ambitious policies. The 2012 Health and Social Care Act created clinician-led Clinical Commissioning Groups responsible for the commissioning of health outcomes [26]. Involving General Practitioners (GPs) in commissioning makes sense because through their decisions and actions they determine the outcomes for patients and also the cost of diagnosis and treatment. Furthermore the new Act promotes the integrated provision of primary, hospital and social care—integrated care.

Big fundamental changes are required for these policies to be successful. Commissioning of patient outcomes and integrated care drives organisational changes, new services and new products; in other words—innovation.

7.2.3 Healthcare System and Stakeholders

The World Health Organisation defines a healthcare system as "all organizations, people and actions whose primary intent is to promote, restore or maintain health" [29]. Tien [28] defines a healthcare system as an integrated and adaptive set of people, processes and products. This definition is incomplete as it ignores that healthcare is managed and delivered through different organisational structures such as Clinical Commissioning Groups, Primary Care practices; Hospitals and Public Health.

In practice healthcare is a complex service system; it combines medical and operational processes that are delivered by people with varied levels of skills and expertise; enabled by technology and facilities across different organisations within a policy framework. Any change in one of these is likely to have an impact on other aspects.

The current model of healthcare in the developed world heavily relies on diagnostics, therapy and care being delivered in hospitals using complex technologies. This requires hospital clinicians to develop a high level of technical skills and patients to be taken out of their community environment. The role of primary care clinicians has become to act as a gateway, referring patients to hospitals for tests and treatment.

Furthermore there is a range of healthcare stakeholders which can be identified according to their position in the system (Table 7.1).

Although one person can represent more than one stakeholder, each group of stakeholders has different motives and interests. All need to be actively involved in the design and implementation of effective healthcare reforms.

7.2.4 Integrated Care and Care Pathways

Integrated care is central to healthcare reforms [14]. Kodner and Spreeuwenberg [17] define integrated care as "a coherent set of methods and models on the funding, administrative, organisational, service delivery and clinical levels designed to create connectivity, alignment and collaboration within and between the cure and care sectors". Integrated care optimises the quality and cost of healthcare for all stakeholders. In practice this means that patients will receive health and social care that is seamlessly delivered between different organisations.

Table 7.1 Healthcare stakeholders

Stakeholder	Position in healthcare system
• Patients	Receiving healthcare
• Patients	Benefitting from healthcare
• Family	
• Employers	
• Wider society	
• Tax payers	Paying for healthcare
• Contributors to private healthcare insurance	
• Insurance companies	
• Healthcare commissioners	Commissioning healthcare
• Clinical commissioning groups	
• Clinicians, carers and support staff	Providing healthcare
• Healthcare managers	Managing healthcare
• Industry	Supplying to healthcare
- Medical devices and products	
- Facilities and infrastructure	
• Academia—research, knowledge and skills	
• Policy makers	Reforming healthcare
• System designers and implementers	

Care pathways are the building blocks of integrated care; they are defined as "structured multidisciplinary care plans which detail essential steps in the care of patients with a specific clinical problem" [4]. A care pathway can be a flow chart showing a sequence of process steps, with people and locations associated. For example the initial diagnosis of Type I diabetes can be made by a GP in primary care; the patient might be referred to hospital for further investigations and therapy including setting up with regular insulin doses.

Care pathways are an important tool for designing healthcare systems in order to capture and communicate current conditions and improvements.

7.2.5 Innovation Challenges

For healthcare to become sustainable requires a shift from being provided in expensive hospital settings to being provided in the community, closer to patients. This can only be achieved through 'root and branch' innovation combining new products with new processes, skills, organisational structures and relationships. Changes have to be designed and implemented as part of a whole system and involve all stakeholders. Furthermore healthcare designers have to consider the adoption and diffusion of innovation and provide a cohesive vision.

Successful innovation methods have to address all these challenges.

7.2.5.1 Adoption and Diffusion of Innovation

Healthcare providers across the world are slow adopters of innovation. In the UK several government reports have investigated this and recommended ways to address this issue with increasing urgency [10]. In a complex system such as healthcare there are a number of related factors responsible for the poor adoption and diffusion such as;

- Healthcare providers have a limited ability and experience to participate in or drive innovation.
- Industry has relied on a 'technology—push' model of innovation by developing products and technologies in isolation, not integrated with healthcare processes.
- Not all stakeholders are involved throughout development.
- Practical aspects for implementation of new processes and devices, such as usability, cost benefit-analysis and organisational changes are difficult to establish and mostly ignored.

7.2.5.2 Vision

There is no blueprint for success; there are no successful examples of sustainable healthcare systems or of healthcare reforms [15]. Models of integrated care provided by private insurers are very difficult to transfer to government systems with rigid structures and entrenched attitudes of different providers. This makes it difficult for policy makers and system designers to develop and communicate a cohesive vision.

7.2.5.3 Role and Direction of Innovation

Healthcare innovation needs to be positioned at the start of the patient journey and medical process in order to shift delivery to the community and to achieve integrated healthcare. This requires an increase of the capability in primary care for assessment and diagnoses, which in turn drives the need for easy to use and affordable technology to be developed.

7.3 Disruptive Innovation and Healthcare

7.3.1 Types of innovation

There are many definitions and classifications of innovation. The UK government recognises that creativity is only the starting point; it defines innovation as "the process by which new ideas are successfully exploited to create economic, social, and environmental value" [2]. It is interesting to note that Schumpeter in the 1930s already recognised that innovation is critical to economic change. In his book 'The Theory of Economic Development', he identified two different responses to change in the business environment: an 'adaptive response' which is an adjustment of existing practice—Incremental Innovation; or a 'creative response' which comes from outside existing practice—Radical Innovation [23].

For the purpose of this chapter we will distinguish 3 types of innovation that are relevant in healthcare: incremental; radical and disruptive innovation.

7.3.1.1 Incremental Innovation

Incremental innovations are improvements of existing products or services based on incremental changes in technology—an upgrade or a next version of a product. Incremental innovation is a response to customer feedback based on needs they can express. Developing these incremental changes is normally well within the company's capabilities and budget; their introduction can be planned. Incremental innovation is associated with a low to medium level of risk.

An example of an incremental innovation in healthcare is the stethoscope. The stethoscope was invented nearly 200 years ago and has been improved continuously due to advances in materials, production processes and additional technologies.

7.3.1.2 Radical Innovation

Radical innovations are products or services that are 'new to the world' and based on breakthrough technologies. Radical innovations can create and address customer unmet needs. Companies that develop radical innovation cannot rely on their existing knowledge and capabilities; they need to do things differently such as recruit people with different expertise, invest in R&D and new manufacturing processes. Potential customers and users cannot provide feedback because the products do not yet exist. Radical innovation is high risk and it is more difficult to plan their introduction to the market.

Examples of radical innovation in healthcare are imaging technologies such as the first Computer Tomography (CT) scanner or the first Magnetic Resonance Imaging (MRI) scanners.

7.3.1.3 Disruptive Innovation

Harvard Business School professor Clayton Christensen coined the phrase 'disruptive innovation' for a phenomenon he first observed in the computer disc-drive sector. He studied other sectors and found the same phenomena. Good companies, which he defined as those who listened and responded to their customers, were developing new features and benefits on an incremental basis. These companies could suddenly be faced by the challenge of a competitor who would introduce a 'simplifying' technology that was not nearly as good but, because it was affordable to customers who previously could not pay for more expensive products, quickly gained market share. The good company was 'disrupted' and only had a couple of options—to abandon that market or to start a new disruption cycle. Many could not react and went bust [7]. Apple and Sony are companies whose initial success is based on disruptive innovations: the personal computer and the transistor radio respectively.

7.3.2 Disruptive Innovation in Healthcare

Disruptive innovation is the most important type of innovation for healthcare reforms because it can deliver the requirements set out in Sect. 7.2.5. It offers affordable solutions that are simpler to use by clinicians and patients in primary care, thereby enabling the shift of healthcare away from hospitals to being delivered in the community. A disruptive healthcare innovation enables medical conditions, which were once exclusively the domain of highly educated physicians to diagnose and treat with complex and expensive device, to be tackled by practitioners with less training.

In The Innovator's Prescription [8] the authors apply disruptive innovation theory to healthcare. They distinguish three integrated elements in disruptive healthcare innovation:

- Technological enabler—the 'simplifying' technology in order to simplify solutions to the problems.
- Business model innovation—consisting of processes, resources, value proposition and profit formula
- Value network or ecosystem that combines these elements.

These three elements have to be developed concurrently and all stakeholders have to be involved throughout the process.

The challenge for designers and engineers in developing simplifying technologies is knowing when this technology is good enough. They do not have a reference as potential users do not use comparable products. It means that designers and engineers have to involve potential users in the development, making sure that the requirements of all stakeholders are met.

The disruptive innovation theory is well described; in healthcare however literature covers hypothetical examples and suggested applications. Designers of medical devices and healthcare systems need practical methods, tools and techniques for developing and implementing disruptive innovations in healthcare.

7.4 Visualisation of Healthcare Systems

7.4.1 Need for Visualisation

Designing and implementing any healthcare change needs a whole-system approach and involve all stakeholders. Stakeholders have to:

- Develop and share a common vision for healthcare
- Interpret information associated with healthcare systems
- Understand the application of new devices
- Understand and evaluate alternative care pathways
- Access reliable forecasts and predictions of outcomes before committing to change
- Agree organisational changes.

In practice this means that designers of healthcare systems and products need to use co-creation and co-development principles. They need to apply a whole system approach because the implementation of new products invariable requires changes in processes and clinical pathways. In incremental innovation or the improvement of current systems, stakeholders have a point of reference. Disruptive innovation provides simplifying technology to a new group of users without previous experience or reference.

Healthcare is associated with huge data sets from a range of sources such as: individual patient records; process and performance data; financial data; personnel and training records; scientific data. All this data is relevant to the design of healthcare systems. However the large quantity of data, different formats and sources make it impossible for stakeholders to use it effectively. They have to rely on visualisation.

7.4.2 Literature Review

7.4.2.1 Visualisation of Information

Visualisation turns data into information. It takes "advantage of the human eye's broad bandwidth pathway into the mind to allow users to see, explore, and understand large amounts of information at once. Information visualisation focuses on creating approaches for conveying abstract information in intuitive ways" [27].

Visualisation methodologies are being applied in biomedical research in order to fully comprehend large data sets. Efroni et al. [11] describe the use of simulation in T-cell maturation at molecular and cellular levels. Eldabi et al. [12] found simulation was beneficial in improving patient flow by showing both the barriers and the potential benefits from a redesigned service. However current simulation methodologies require specialist skills and resources and the results are not accessible to all stakeholders.

7.4.2.2 Visualisation of Complex Systems

Using visualisation methods to deal with complex systems might appear to be commonsensical; after all the saying goes ‘a picture paints a thousand words’. Literature confirms that visualisation methodologies are accepted and successfully applied in sectors such as the manufacturing industry to help understand the design and assembly of components into complex products such as aircrafts or cars [9]. Visualisation methods are furthermore used in diverse domains such as the development of strategy, business processes, risk analysis, protein development and analysis of fuzzy data. Mostafa first describes developing visualisation for understanding complex system in particular using multi-agent systems relating to food intake [21]. Fernando describes the development of an IT infrastructure that captures a complex network of relationships and interactions in order to support urban planning for sustainable cities [13]. This system is operational at the ThinkLab in Salford University and allows greater interaction, understanding and better decision-making between multiple stakeholders.

There is a lack of dedicated studies on the practical application of ‘complexity theory’ in healthcare. Plsek and Wilson [22] suggest considering healthcare as a complex adaptive system rather than as a machine. Chahal and Eldabi [6] recognized the scale of the complexity of UK healthcare and propose to use hybrid simulation but they do not deal with the challenge of how the results can be of practical value to a diverse range of stakeholders.

7.4.2.3 Visualisation of Care Pathways

In healthcare there is some work on the use of visualisation in analysing the flow of pathways or through departments for instance in emergency admissions [18]. Wong describes the use of visualisation in workflow in Radiology [30]. Others are planning to use visualisation for resource planning in community care [19]. The Map of Medicine (http://healthguides.mapofmedicine.com) provides an online resource for healthcare professionals that includes ‘best practice’ pathways for diseases and conditions based on evidence. However these pathways do not allow comparative analysis as they do not provide additional information such as performance data, cost constraints, organisations involved and furthermore do not allow options for re-design based on new devices, medication or processes.

The NHS collaborated with a Canadian company to develop the Scenario Generator web-portal as a commercial application (http://www.scenario-generator.com). Its focus is on simulating service change due to demand or provision and uses live system data. It does not include the modeling of change due to new technologies or devices. Furthermore it is not accessible to all stakeholders.

Literature on the application of visualisation methods in the design of whole healthcare systems is surprisingly scarce. We postulate this has to do with a lack of the right multi-disciplinary approach in research combined with a range of technologies and techniques that have to come together, such as data mining, agent-based modelling, simulation and visualisation.

7.4.2.4 Virtual and Augmented Reality

In Virtual Reality (VR) the users' perception of reality is completely based on virtual information. In Augmented Reality (AR) the users is provided with extra computer generated information that enhances their perception of reality [5]. In architecture VR can be used to show a walk-though simulation of the inside of a new building; AR can be used to show a building's structures and systems super-imposed on a real-life view.

In healthcare AR can be used to provide guidance during diagnostic and therapeutic interventions e.g. during surgery. Magee et al. [20] for instance describe the use of augmented reality for medical training in simulating ultrasound guided needle placement.

7.4.2.5 Co-designing Services

Co-designing brings people together to share their experiences with designers facilitating and supporting users in developing solutions for themselves. There is an overlap between co-design and service design: in co-designing users are involved in the design of new services [16]. Blomkvist and Holmlid [3] describe how co-design is used in emergency departments in hospitals. Tan and Szebeko [25] describe how co-designing is used for people with dementia.

In disruptive innovation the term 'users' needs to include all stakeholders.

7.4.3 Specification for Visualisation Systems

This brief literature review confirms the validity of combining disruptive innovation principles with co-design methods and visualisation technologies. However this combination has not been applied yet.

Visualisation-based technologies can effectively support disruptive innovation products and services in healthcare because they:

- facilitate the modelling of complex systems
- allow all stakeholders to interact with alternative models
- can be used throughout the different phases of the innovation process.

These visualisation technologies need to provide an integrated view of products, people, organisations, processes and services.

7.5 Conceptual Visualisation Technologies

Researchers at Cranfield selected a new portable ultrasound imaging device to develop and validate conceptual and prototype visualisation technologies. Portable ultrasound could be used at the early stages of the medical process for assessment

Fig. 7.1 GE healthcare's Vscan. Reproduced with permission of GE healthcare ©GE Healthcare

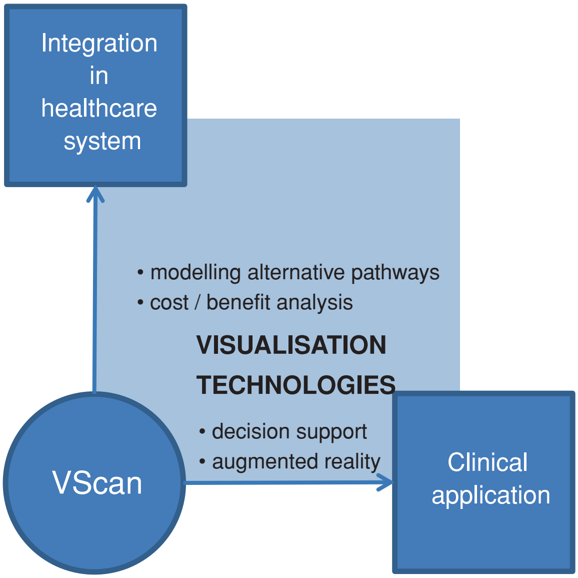
and diagnosis in primary care. The research team chose to use this device in a practical bottom-up approach to explore alternative pathways; business models and evaluating the impact of the device across healthcare organisations.

7.5.1 GE Vscan Exemplar Disruptive Innovation

In 2010 GE Healthcare introduced the Vscan, a highly portable ultrasound imaging device (Fig. 7.1).

It is a pocket-sized ultrasound device that could potentially become a disruptive innovation as it is based on 'simplifying' technology and more affordable than hospital-based ultrasound scanners. This device can be used in the diagnosis of a range of medical conditions, such as aorta aneurysm, deep venous thrombosis and gall stones. Using a device within the primary care will reduce the cost of procedures, free up capacity of much larger complex imaging systems at hospitals, speed up the diagnostic process and be less stressful for patients. Whilst Vscan has the potential to deliver the benefits that healthcare providers need, there are challenges to overcome before its widespread adoption in primary care. A major challenge is the ability of healthcare professionals, without experience in ultrasound scanning, to use the device with relatively little training. Compared to other medical imaging technologies, ultrasound scanning—or sonography—is an interactive process as the operator needs to continuously interpret images for positioning, navigating and assessing of abnormal tissues and structures. This requires a high level of skill that can only be acquired after a long period of training to cover all organs and conditions. Making an ultrasound scanner more portable or reducing its purchase price has no impact on the level of skill that is required.

Fig. 7.2 Scope of research



The Vscan is an ideal product for researching visualisation technologies. It can support the diagnosis of conditions in a range of body systems. Furthermore as a diagnostic device it is fundamental in the medical process. Findings can be extrapolated to other conditions and devices, offering the potential for future developments to be applied at generic levels.

7.5.2 Scope and Roadmap

The GE Vscan was used as an exemplar to explore the use of visualisation methods for integrating a new disruptive innovation device in the healthcare system by modelling alternative pathways and analysing cost/benefits for each. Visualisation was also used to facilitate the clinical application of the device through decision support systems and augmented reality. Figure 7.2 shows the scope of the research in these two directions.

The initial phase of the research covers the development of conceptual visualisation technologies. In the next phase practical prototypes are developed that can be used on portable platforms such as smart phones and tablets. Further research continues in the two directions outlined as can be seen in the roadmap in Fig. 7.3.

7.5.3 Mapping Alternative Pathways and Business Models

Business model innovation is one of the elements in disruptive innovation. Care pathways are the building blocks of healthcare systems. Disruptive innovations require new pathways that are likely to cross organisational boundaries. In turn

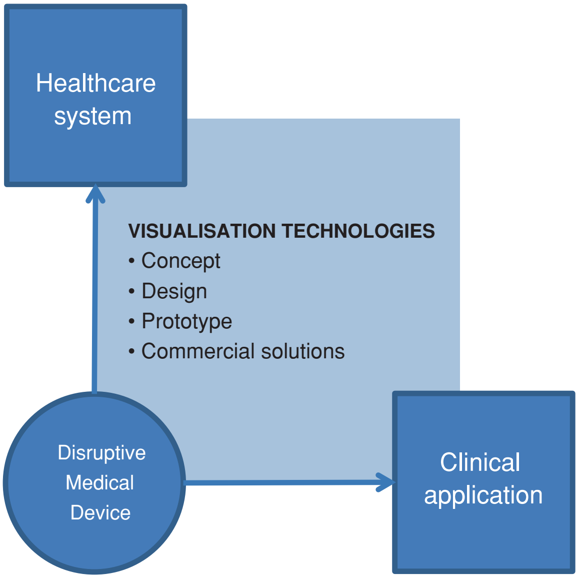


Fig. 7.3 Research roadmap

this might lead to changes in commissioning and reimbursement, in other words to different business models. For the purpose of the remainder of this chapter we will use the terms 'business model' and 'pathway' interchangeably.

7.5.3.1 Methodology

The literature review provided a basis for semi-structured interviews with subject matter experts including: GPs, a consultant radiologist, a senior surgeon with healthcare management experience, a medical director of a Primary Care Trust, an expert on clinical commissioning and a provider of continuous professional development for GPs. Through these interviews we developed the "AS-IS" model for ultrasound scanning using Object-Process Methodology (OPM). We identified the issues involved in current scanning practices in the UK.

OPM could be considered a visualisation methodology as it brings together all "the system lifecycle stages (specification, design, and implementation) within one frame of reference, using a single diagramming tool, a set of object-process diagrams (OPDs) and a corresponding subset of English, called object-process language (OPL) that is intelligible to domain experts and nontechnical executives who are usually not familiar with system modelling languages" [24].

We developed four alternative pathways as potential improvements through multi-disciplinary brainstorming sessions. Each alternative was represented using OPM models and validated by stakeholders. Furthermore an MS Excel based software tool was developed for cost/benefit analysis in order to compare the alternative pathways. Detail costs for process steps were provided by subject matter experts.

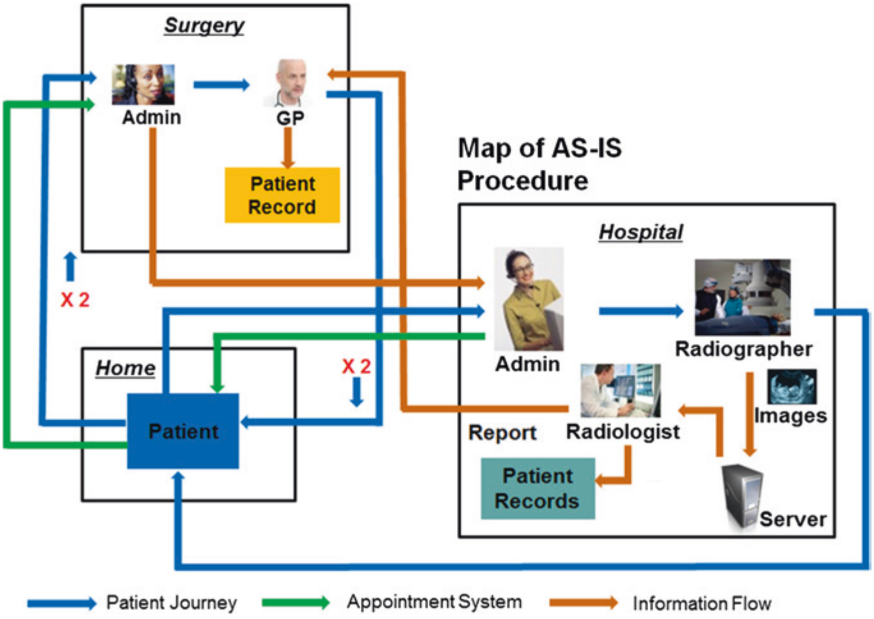


Fig. 7.4 Current procedure for ultrasound scans

7.5.3.2 AS-IS Model

The AS-IS model describes the typical journey of a patient presenting a number of symptoms. Based on these the GP decides that an ultrasound scan is required to obtain or support a diagnosis. The GP assumes that the condition is not critical and therefore no emergency procedures are invoked. The model concludes when at the final consultation therapy is started, which is outside the scope of this study.

The process starts with the patient contacting their local surgery to make an appointment to see their GP. The availability of the GP is checked by the surgery receptionist, who informs the patient as to when she or he should show up for the initial consultation. Upon arrival, the patient is booked in at the reception desk by the surgery administrator (Fig. 7.4).

During the initial consultation, the GP decides that an ultrasound scan is required. A request is made to the nearest hospital with the appropriate resources. The patient's records are updated and the patient returns home. The hospital contacts the patient with a suggested appointment; the patient then has to contact the hospital administration to confirm that they are available to attend. The waiting time depends on the current load of the radiology department and the availability of sonographers and equipment to complete the scan. On arrival at the hospital, the hospital administrative assistant books the patient in. At the allotted time, the patient is admitted to the radiology centre, where they will be prepared for the procedure. The sonographer then performs the scan and uploads the images on the radiology server for later analysis and reporting. The patient is then discharged and returns home. At some point, the patient's ultrasound images will be downloaded by a departmental radiologist or diagnostic sonographer, who completes the analysis and compiles a report on the findings. This report is sent by (physical or electronic) mail to the GP, and the patient's hospital records are updated with the results. Upon receipt of the report, the GP concludes the diagnosis and the surgery receptionist contacts the patient to return to the practice for a follow-up consultation. The patient travels from home to the surgery and books in via the administration system as before. During the follow-up consultation, the GP advises the patient on any further follow up treatment that may be necessary. The patient surgery records are updated to reflect the outcome and further treatments necessary. The patient subsequently returns home.

The patient's journey is summarized in Fig. 7.4, which shows the physical movement of the patient between home, surgery, and hospital, together with the flow of information throughout the process. However, this diagram does not represent the personal and social cost experienced by the patient. These may include travelling costs using one's own or public transport, time off from employment and sundry costs, such as payment for parking at the hospital, which adds another dimension of complexity.

In a typical scenario for a diagnostic procedure that on average lasts 20 min, patients have to travel 24 miles and will experience 24 service point contacts. For a non-emergency the process will take 17 days to complete from the initial visit to the GP the final consultation.

7.5.3.3 Potential Improvements

The areas that need improvement in the AS-IS model are defined below.

- Costs—scanning procedures in hospitals are expensive. Therefore, reducing the number of patients who need to receive a scan in hospital would reduce costs for commissioners.
- Waiting time—too many patients are sent to the hospital for scanning. Some of our experts estimate that 80 % of scans did not reveal any issues. Hospitals become too crowed and the waiting time to perform a scan is very long (up to six weeks). Due to the waiting time for a scan and sequential confirmation of the diagnosis, diseases are not treated at an earlier stage. This can be dangerous for patients' health. Diagnosing patients' disease at an earlier stage through a new device would reduce this bottleneck in the healthcare system.
- Patient experience—Avoiding a journey to the hospital would be a great improvement in the patient experience. It would also eliminate the parking cost of the hospital, which appears as the first reason given by patients to avoid hospital.

Based these improvements and using the Vscan a number of alternative pathways were developed whilst taking into accounts the needs of key stakeholders; including:

- Patients—reducing the distance travelled and the time taken from the initial consultation to the start of treatment.

- GPs—having access to diagnostic information earlier will increase control over patient journey and outcomes resulting in better quality of care at lower costs.
- Clinical Commissioning Groups—reducing the overall budget.

7.5.3.4 Alternative Pathways

Existing ultrasound scanners employed in radiology departments in hospitals are expensive, complex to operate and are not designed for mobility. Therefore, the existing process is designed around bringing the patient to the resource. The portability and lower cost of Vscan makes it possible to shift ultrasound scanning to the community by taking the resource to the patient and making it more widely available.

In order to be able to develop the alternative pathways, four criteria have been specified. The first criterion is technical limitations of the Vscan. What is the impact of any technical limitation? If care pathways require features that are not provided by the device, then they cannot be qualified. The second criterion is the competency of the people using it. If the user of the Vscan is able to use it without external assistance, then this criterion is validated. The third criterion refers to medical and legal issues. If some restrictions in this regard exist, then the care pathway is not qualified. Finally, the fourth criterion is about organizational issues. If drastic organizational changes that are incompatible with surgeries' actual organisation are needed, then the care pathway is not qualified.

Accordingly four care pathways were developed:

- Care pathway 1: GP completes scan at surgery
- Care pathway 2: Sonographer visits surgery each week
- Care pathway 3: Diagnostic sonographer or radiologist visits surgery each week
- Care pathway 4: Mobile sonographer visits patient at home.

The following section focuses on Care pathway 3 as it could be implemented in the short term as it does not require GPs to be trained. Furthermore it was considered to be the most beneficial in terms of patient satisfaction and cost savings.

7.5.3.5 TO-BE Pathway 3

Care pathway 3 is based on the services of a visiting diagnostic sonographer, who is qualified to capture images, analyse the results, and provide the GP with a report on the findings. Figure 7.5 provides an overview of the overall system. Patient reports will be completed as a batch for all patients seen during the day of the sonographer's visit. On receipt of the report, arrangements may be made for the patient to return to the surgery for final consultation and start of remedial treatment. A variation of this process may make it possible to complete the report immediately after the image capture while the patient is still at the surgery.

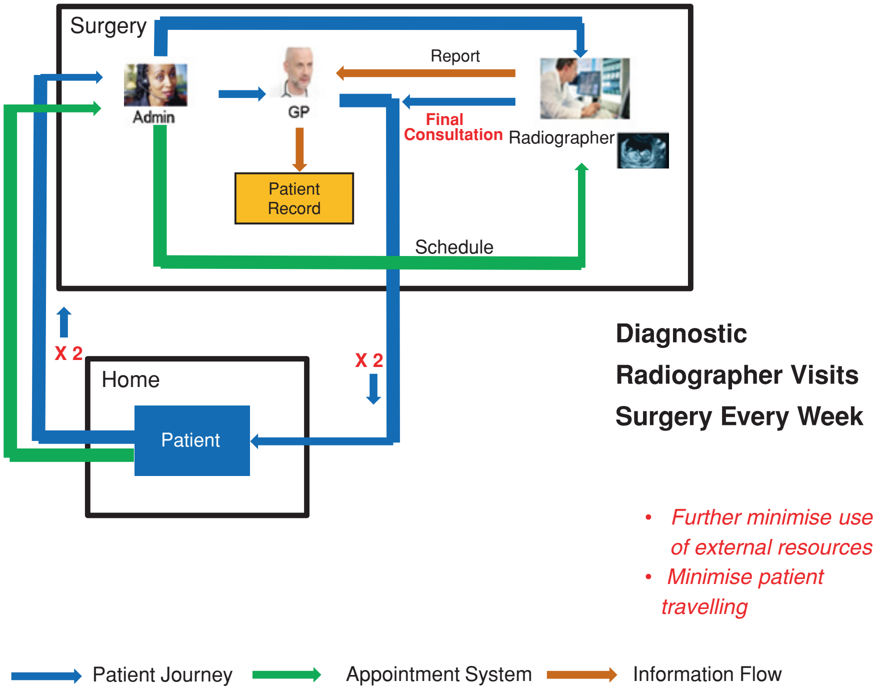


Fig. 7.5 TO-BE pathway 3

This has the advantage of being able to start any remedial treatment straight away and reducing the number of patient journeys to two but will depend on the workload and schedule of the sonographer.

Figure 7.6 is a snapshot of an Object-Process CASE Tool (OPCAT) screen, representing all stakeholders involved in Patient Treating process. People, agents in OPM terminology who handle the process are GP, Surgery Receptionist, and Visiting Diagnostic Sonographer. The instruments required are Scanner, GP Server and Laptop. It also shows objects affected by the Patient Treating process: Patient, Patient Medical Status and Patient Record. Figure 7.6 shows the sub-processes of the Initial Consulting process are the Initial Appointment Setting, Surgery Arriving, Initial Consulting Executing, Sonography Appointment Setting and Leaving. This OPD illustrates one of the most interesting aspects of OPM modelling. It shows how sub-processes affect Patient Location and Patient Medical Status by changing their states. The state of Patient Location is affected by the Surgery Arriving process, so it changes from home to surgery. Similarly, Patient Medical Status changes from not diagnosed to in need of scan during the Initial Consulting Executing process. Initial Consulting Executing generates an object called Scan Request. This last step requires executing the next process, Sonography Appointment Setting.

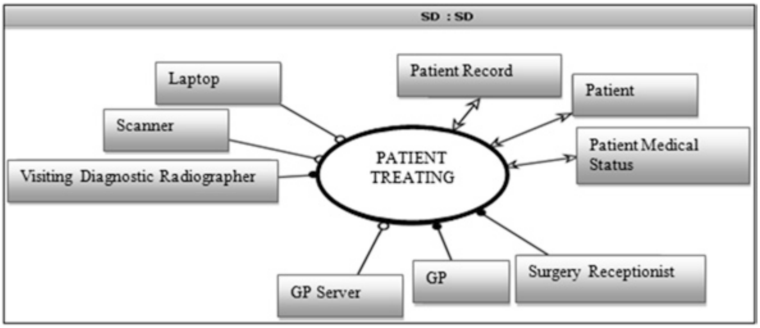


Fig. 7.6 Map of stakeholders and agents in diagnostic process

7.5.4 Analysing Costs and Benefits

In order to develop a tool to compare cost/benefits for each of the pathways we considered the patients' and the healthcare system's perspectives. The tool is based on Microsoft Excel and consists of: inputs; calculations using Monte Carlo methodology and outputs.

7.5.4.1 Inputs

We identified the following inputs:

- Number of patient requiring ultrasound scan per day
- Patient Journey
- Patient Waiting Time
- Duration of investigation
- Hourly Cost of Specialist
- Administration Charges.

7.5.4.2 Calculations

Considering the variations in number of patients per day and in duration of the ultrasound investigations we applied the Monte Carlo methodology for our calculations. This used two types of data: (1) minimal, maximal and typical number of patient per day and (2) Random time for scan. Using prepared macros for Monte Carlo simulation provides an annual number of patient requiring scan and time required for scanning. Then the Monte Carlo method is used again to determine how much time is needed to perform scanning for each patient. Minimal, maximal and typical values are fixed (based on specialist's interviews). Finally all the time per procedure for each patient are added to generate the total time needed to perform ultra-sound scanning per year.

Fig. 7.7 Comparing annual savings for each care pathways

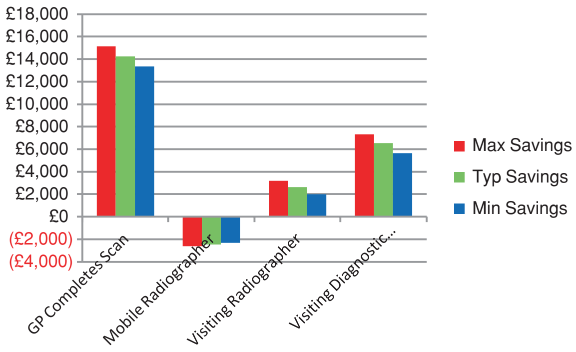
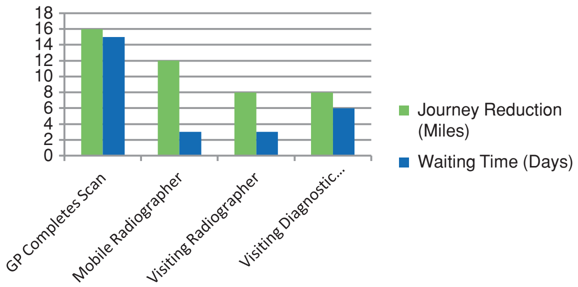


Fig. 7.8 Comparing patient benefits for each care pathways



Patient benefits are calculated by comparing Patient Journey and Patient Waiting Time of the current procedure with obtained Patient Journey and Patient Waiting Time for each of the pathways.

7.5.4.3 Outputs

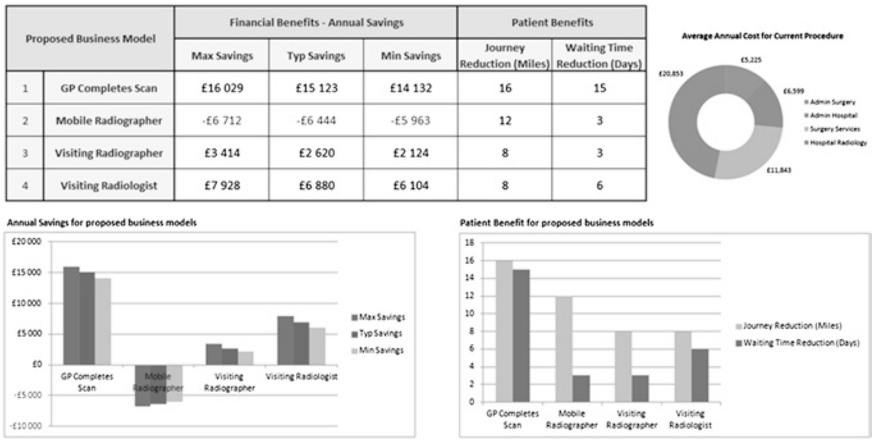
By comparing costs of each of the pathways with the cost of the current procedure; savings relating to each of the alternatives are obtained as shown in the Summary Sheet (Fig. 7.7).

Patient benefits are calculated by comparing Patient Journey and Patient Waiting Time of the current procedure with obtained Patient Journey and Patient Waiting Time for each of the pathways (Fig. 7.8).

Figure 7.9 provides a 'dashboard' overview of all the parameters of the cost/benefit analysis.

7.5.4.4 Results

The action research was labour intensive; it took a team of five post-graduate researchers 15 man-months to produce alternative pathways with cost/benefit analysis for each alternative. Although healthcare practitioners could understand the



Proposed Business Model		Financial Benefits - Annual Savings			Patient Benefits	
		Max Savings	Typ Savings	Min Savings	Journey Reduction (Miles)	Waiting Time Reduction (Days)
1	GP Completes Scan	£16 029	£15 123	£14 132	16	15
2	Mobile Radiographer	-£6 712	-£6 444	-£5 963	12	3
3	Visiting Radiographer	£3 414	£2 620	£2 124	8	3
4	Visiting Radiologist	£7 928	£6 880	£6 104	8	6

Fig. 7.9 Dashboard view of costs /benefit analysis for alternative pathways

alternative pathways and use the cost/benefit tool, the time and resources required are prohibitive for practical applications.

It was interesting to note that if GPs were able to use the Vscan themselves this would result in a shortest time to diagnosis and the biggest cost reduction. Patients would have to travel less. Figure 7.9 shows that if GP were able to use the Vscan would result in annual savings of £14 k. Patients would have to travel 18 miles less and their waiting time would be reduced by 15 days.

However this is cannot be implemented immediately due to lack of skills in GPs and extent of training required. Considering the potential benefits of this scenario led us to develop guidance and diagnosis support system for a relatively straight forward condition such as gall stones for which little training will be required.

7.5.5 Decision Support System

Clinicians and other healthcare professionals without any previous experience in ultrasound will not be able to use Vscan without extensive training as explained in 4.1. This third visualisation technology aims to address that issue. It supports the application of Vscan in clinical practice, along the horizontal axis in Figs. 7.2 and 7.3. Rather than training clinicians on sonography for a range or organ systems and conditions we selected one common condition to develop an augmented reality based guidance and decision support system. In consultation with experienced GPs and radiologist we chose gall stones. This is a relative common condition; an early diagnosis leads to a direct referral to surgeons, by-passing further radiological examinations, and earlier therapeutic interventions.

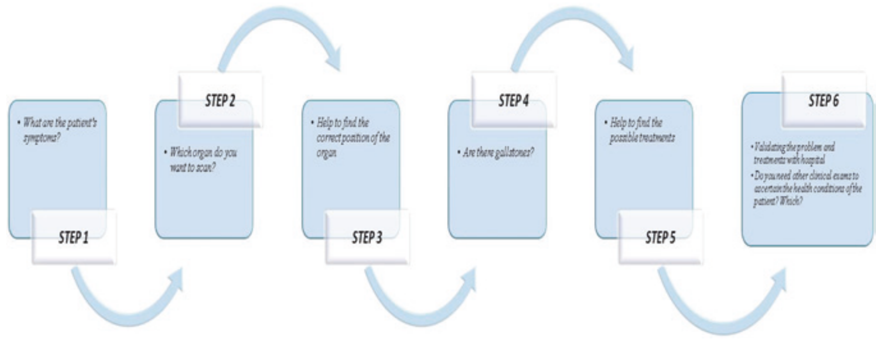


Fig. 7.10 Steps in diagnosis support system

7.5.5.1 Conceptual Development

The conceptual visualisation tool was developed using Microsoft Excel. It is an interactive system that consists of a number of screens throughout the diagnostic process. Figure 7.10 shows the sequence of the steps.

After the initial assessment the GP suspects that the patient might be suffering from gallstones. Figure 7.11 shows the first screen to capture the patient's symptoms.

The next screen helps to understand which organ might be involved (Fig. 7.12).

This screen also provides the clinicians with guidance on where to find the organ and how to position the Vscan.

The last screen provides reference images showing a healthy gall bladder and different types of gall stones (Fig. 7.13). This screen also contains advice on possible next steps such referral to hospital for further investigation or surgery.

7.5.5.2 Initial Validation of Conceptual Visualisation Technologies

The conceptual visualisation technologies were validated by GPs, a consultant radiologist and healthcare managers. It was estimated that GPs could use this system in combination with Vscan device after 1/2 day training. Furthermore these stakeholders recognised the generic character of this system. Not only could it be applied to support ultrasound imaging of different organs and conditions; it could also be used for other diagnostic devices.

7.5.5.3 Discussion

At the conceptual phase of development visualisation technologies show their potential to support the application of Vscan in clinical practice and its integration in the healthcare system. Visualisation helped stakeholders to understand how pathways can change by using Vscan and what the potential costs and benefits are.

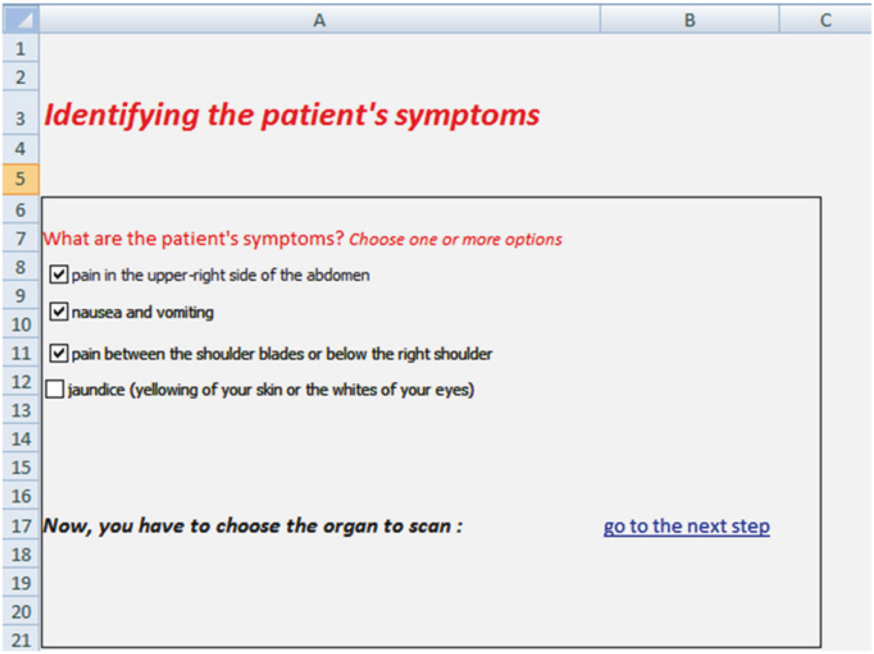


Fig. 7.11 Patient's symptoms

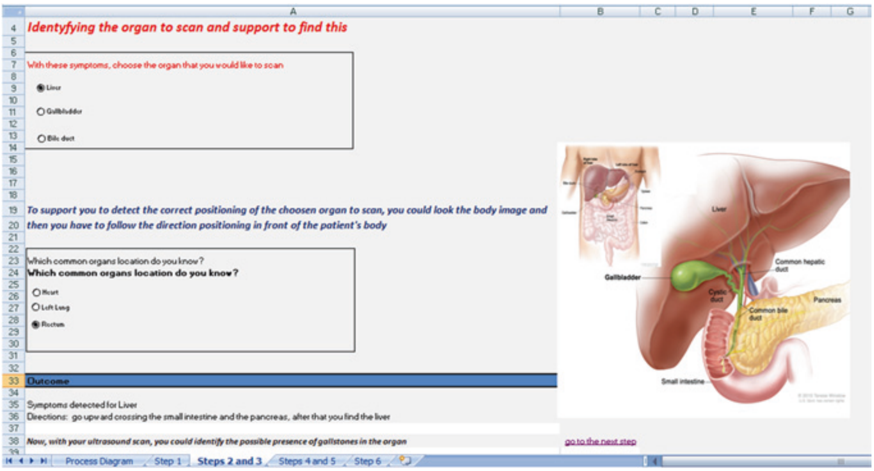


Fig. 7.12 Possible location of gall stones

However it is also clear that stakeholders would not use these conceptual technologies themselves as they: are not user-friendly; take too long to set-up and show results; are not easily accessible, do not provide an integrated view of care pathways with cost/benefit information.

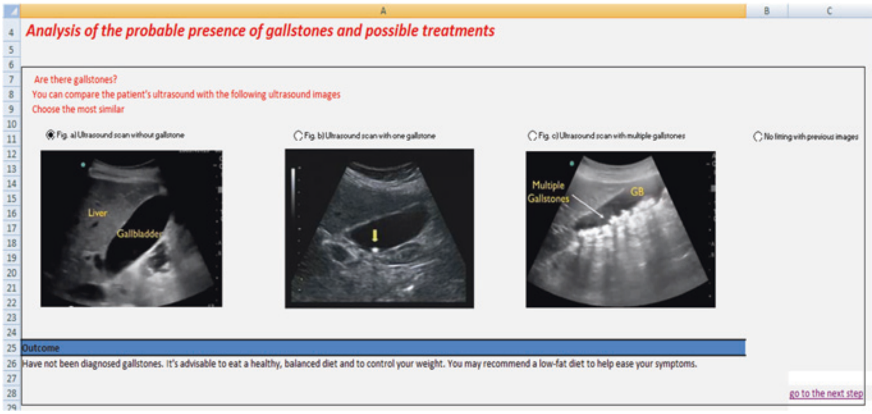


Fig. 7.13 Reference images

7.5.6 Prototype Development

After the encouraging feedback received during the initial validation of the conceptual technologies we decided to continue the project by developing two web-based software prototypes:

1. Cost/benefit analysis of alternative pathways
2. Decision-support-system for clinicians without experience of ultrasound to use a portable device for specific conditions e.g. gall stones.

Both prototypes can be accessed through smart-phones, tablets, laptops or desktop computers. In developing these prototypes we continued to use the co-design approach and worked with stakeholders.

7.5.6.1 Prototype Cost/Benefit Analysis

The prototype cost/benefit analysis software supports designers of healthcare processes and managers in evaluating and implementing alternative pathways. The prototype has been designed for the implementation of portable ultrasound devices for assessment and diagnosis in community settings. It has been designed as a platform that later can be customised for other diagnostic technologies e.g. blood tests.

The opening screen presents the user with an overview flowchart of the alternative pathways for portable ultrasound in comparison with referral to hospital. It allows the user to enter parameters specific to a GP practice such as number of patients, AS-IS waiting time and costs (Fig. 7.14).

Using the same method of calculation as the conceptual model presented in Sect. 7.5.4.2, the user is presented with information on costs for each of the alternatives. The data is presented in a highly visual way which facilitates understanding and communication amongst stakeholders (Fig. 7.15).

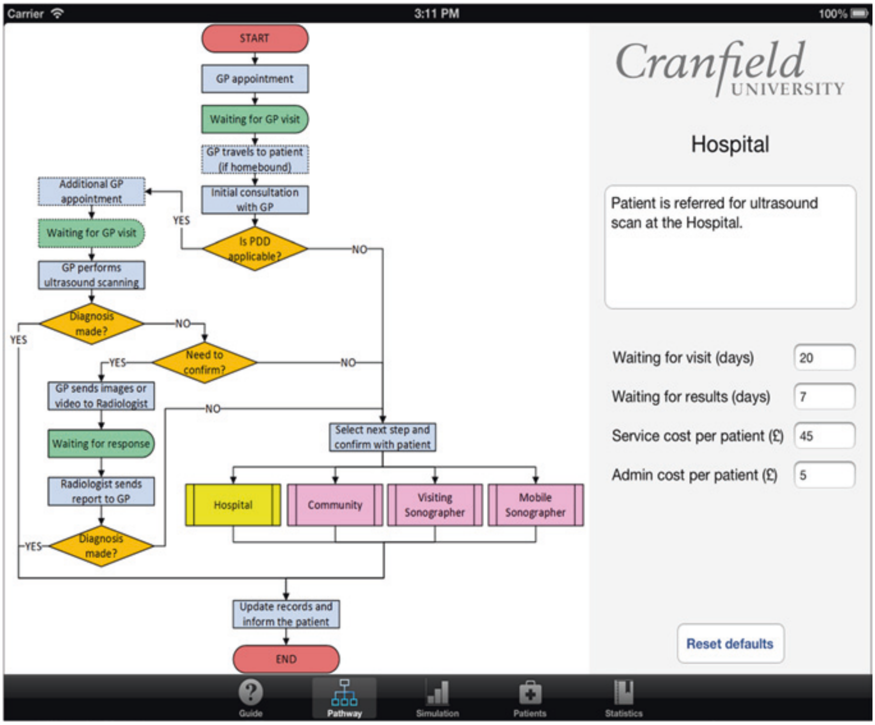


Fig. 7.14 Cost/benefit analysis opening screen

Importantly the user can also see the impact of using ultrasound in GP surgeries on patients in terms of reduced waiting time before receiving a diagnosis and the impact on patient anxiety (Fig. 7.16).

The combination of information on costs and impact on patients allows healthcare designers and managers to make an informed decision on the most suitable alternative pathway. Once implemented, they can further monitor this pathway as the prototype presents performance data. This allows adjustments to be made (Fig. 7.17).

7.5.6.2 Prototype Decision Support System

The prototype Decision Support System aims to support clinicians with limited or no experience in using ultrasound to use a portable device for assessing and diagnosing a relative straightforward condition such as gall stones. We assumed that once clinicians experience the impact early diagnosis has on cost and quality of patient care, they will adopt the device and explore other its use in other conditions. We designed the prototype therefore as a platform that can be customised. Furthermore we recognised that it is important that clinicians update and maintain their expertise. Therefore we included a training module that allows self and peer assessment.

Figure 7.18 shows the overview of the work flow of the decision-support-system.

Fig. 7.15 Cost analysis for alternative pathways

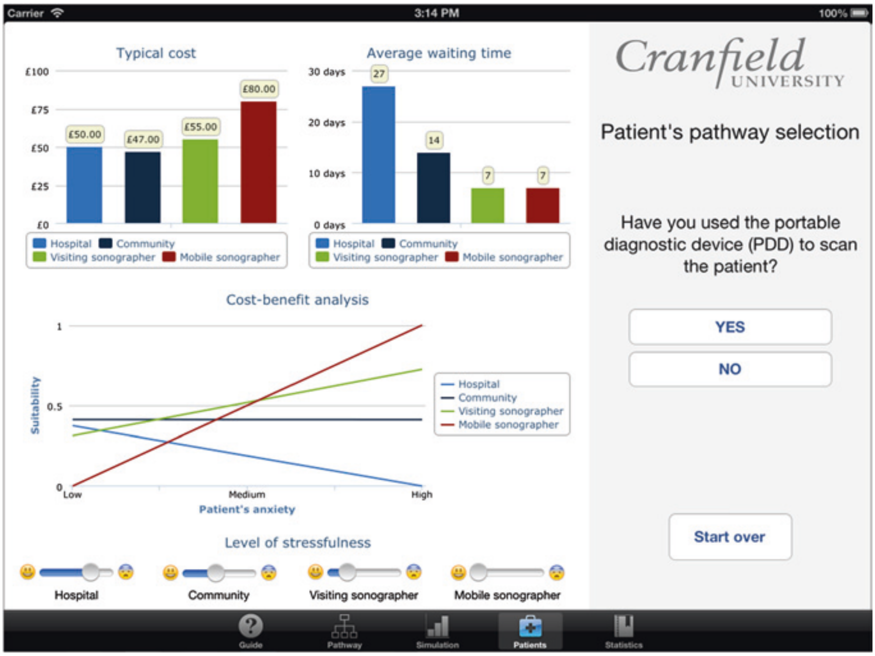


Fig. 7.16 Analysis of patient impact of alternative pathways

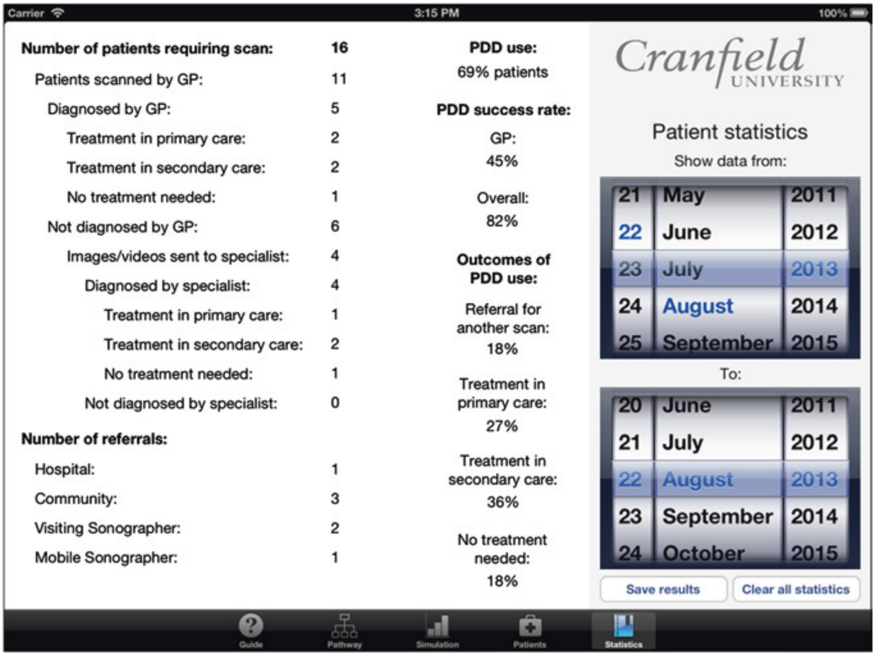


Fig. 7.17 Performance indicators for monitoring

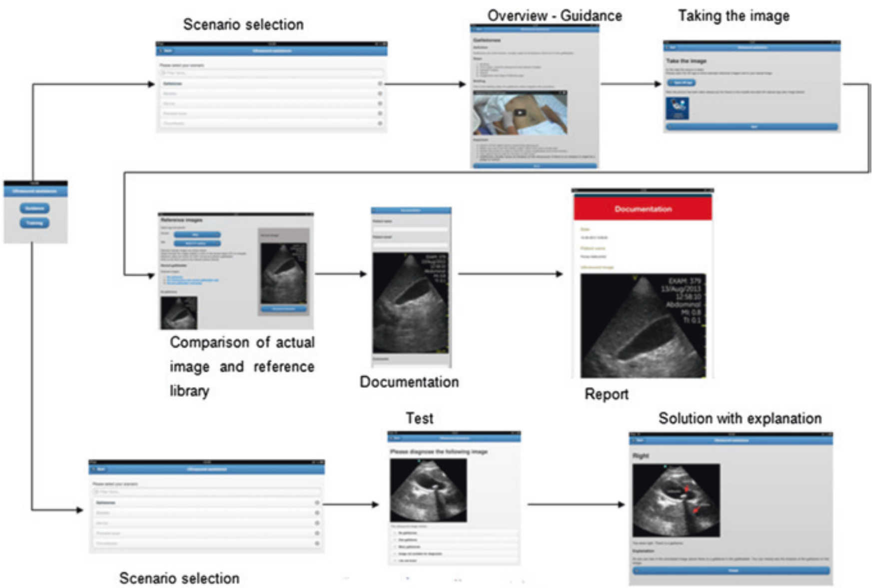


Fig. 7.18 Work flow of the decision-support-system

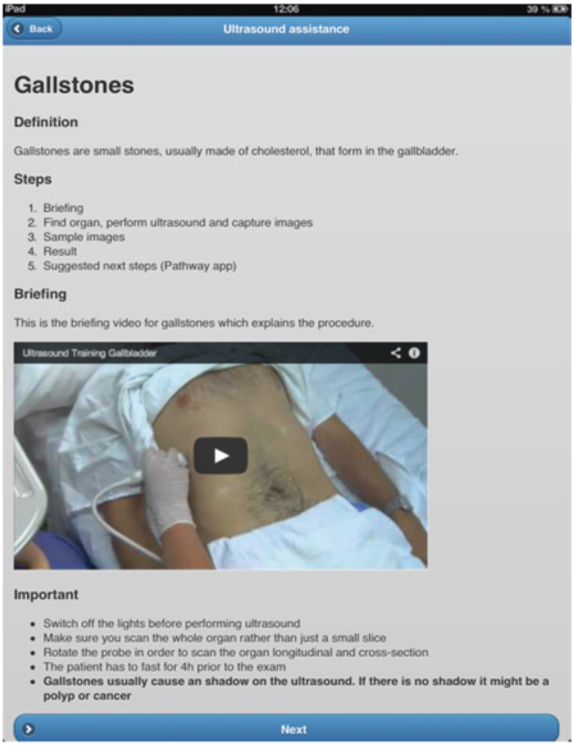


Fig. 7.19 Guidance screen

Initially the clinician is given background information about gall stones and receives guidance on where to position the ultrasound probe. Figure 7.19 shows the Guidance screen with a link to a video demonstration of an examination for gall stones.

After locating and exploring the gall bladder the system then presents the clinician with reference images of healthy and deceased organs so they can assess their patient (Fig. 7.20).

Once the clinician is satisfied they can capture their observations, conclusions and recommendations and communicate these by email with attached images or short videos of the ultrasound scan (Fig. 7.21).

7.5.6.3 Initial Validation

Both prototypes were presented to and used by stakeholders including clinicians and managers. We received very positive feedback such as "Great potential of revolutionising the way healthcare works", "cuts down the number of unnecessary referrals dramatically" and "very logical and user friendly".

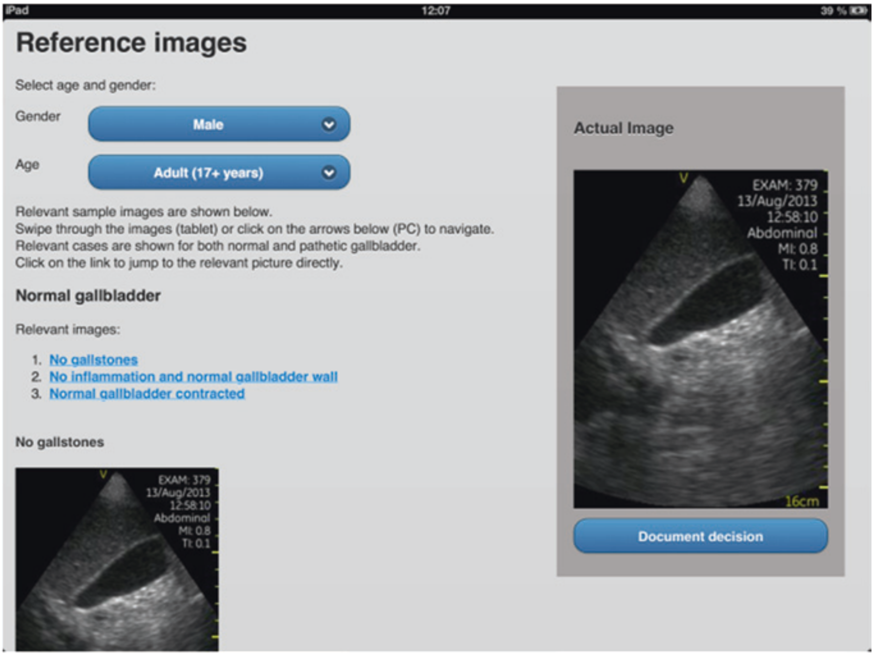


Fig. 7.20 Reference images

7.5.7 Discussion

The project demonstrates that visualisation is relevant for medical practice and healthcare system design. Visualisation helped stakeholders to understand how pathways can change by using Vscan and what the potential costs and benefits are. Not only do visualisation technologies show their potential in supporting the application of Vscan in clinical practice and its integration in the healthcare system. It is likely that visualisation technologies can also support other diagnostics and conditions and be applied throughout healthcare.

7.6 Future Developments

The prototype visualisation technologies need further development and validation. Beyond portable ultrasound scanning for the diagnosis of gall stones, applications need to be developed for other conditions and diagnostic technologies.

7.6.1 Mapping and Evaluating Pathways

Visualisation technologies need to become user-friendly so that stakeholders can use these themselves. They should be able to easily access these technologies e.g.

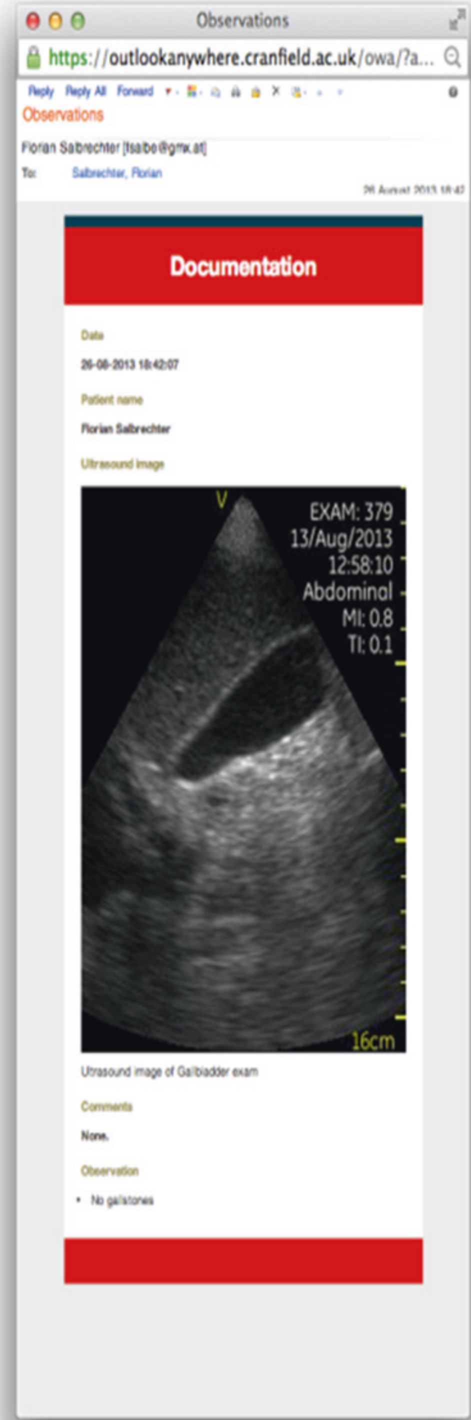


Fig. 7.21 Documentation

by using handheld device such as smart phones and tablets. Designing of alternative pathways needs to be combined with cost/benefit analysis in an integrated package. Patient, process, product and 'live' system data should be incorporated making it possible to more accurately predict outcomes. These systems could also be used to advise patients on best pathway e.g. hospital C offers a shorter length of stay for a certain intervention with better outcomes than hospital B.

7.6.2 Decision Support System

The generic character of the decision support system needs to be preserved. The application in the diagnosis of gall stones needs to be refined before it can be validated in clinical trials. Then the systems should expand in lateral and vertical directions. Laterally by developing further applications for other conditions or organ systems e.g. heart failure or as obstetrics. Vertically by providing more information on alternative diagnosis or advice on next steps.

Ultimately the system can be developed into a genetic diagnosis support system than can be configured for different organs or conditions.

7.6.3 Developing Disruptive Healthcare Innovation

From a manufacturers' point of view visualisation technologies can help the commercialisation of a device, such as Vscan that is already in the market place. Marketers can demonstrate costs and benefits to potential customers. However to get the most benefit these technologies should be applied during the development of disruptive innovations with all stakeholders. That way these technologies ensure that the new product or process is implemented faster thereby increasing adoption and diffusion.

7.6.4 Healthcare Systems Design

Visualisation technologies are particular relevant for but not constraint to disruptive innovation, they could enable incremental or radical innovation too. Combining data mining with agent-based modelling could lead to a tool for whole healthcare system design that predicts the outcome of alternative scenarios in a way that is understandable for all stakeholders. This combination would therefore facilitate informed decision-making and ensure stakeholders 'commitment to changes'.

Applying Virtual Reality technologies such as immersive environments, would allow stakeholders to co-design future healthcare systems. Another possibility is combining healthcare visualisation with serious games technologies thus allowing stakeholders to play with different aspects of healthcare systems and explore alternative scenarios. This could include for instance the impact of new policies or an assessment of a new type of health professional such as nurses with diagnostic capabilities.

7.7 Conclusion

Disruptive innovation is important for sustainable healthcare but brings with it big challenges. For it to have an impact throughout a healthcare system requires changes in healthcare processes and organisations. All stakeholders have to be involved in developing and implementing disruptive healthcare innovations. This requires specific methods and technologies.

This project demonstrates that portable ultrasound in primary care is a potential disruptive innovation that: enables integrated pathways; reduces cost of healthcare and increases patients' experience. Our research has shown that enabling technologies based on visualisation reduce the need for training of clinicians and provide information on cost/benefits for implementation. Visualisation technologies are relevant for clinical practice and for the design of healthcare pathways and systems. Further research is required to develop and validate practical prototypes.

Visualisation technologies should be applied in the early development stages of potential disruptive innovations but can also be applied in other types of innovation or in the design of healthcare services.

Ultimately visualisation can be an enabling technology for the design and implementation of sustainable healthcare systems.

Acknowledgements The presented work has been carried out as part of the VISIONAIR project, which is funded by the European Commission under grant agreement no. 262044 (www.infra-visionair.eu).

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Part II
Nursing Training, Health Literacy, and Healthy Behaviour

Chapter 8
Virtual Simulations and Serious Games in Community Health Nursing Education: A Review of the Literature

Pamela Stuckless, Michelle Hogan and Bill Kapralos

Abstract The recent shift in healthcare delivery from that of the hospital to the community calls for skilled community health nurses. The role and practice of community health nurses differs from that of a nurse clinician. Unlike the skills required for that of a nurse clinician, much of the skills required for community health nursing and their application cannot be developed and practised within newly developed and highly innovative practice laboratory facilities where the focus of patient care is the individual. Virtual simulation (and serious gaming) presents a viable, cost-effective training option for community health nursing trainees, providing the opportunity to practise within an interactive, engaging, and safe environment. In this chapter we review and examine the use of virtual simulation (including serious gaming) in health care education with a particular emphasis on community health nursing. Findings demonstrate that students and nursing educators recognize the value of virtual simulation in community health nursing education. Best practices in simulation development indicate that a framework that guides the design, implementation, and evaluation should be employed. Assessment methods of student learning have been suggested however, further research is needed on assessment techniques and learning outcomes to demonstrate that virtual simulation may be a sound pedagogical tool.

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8.1 Introduction

Recent health care reforms have resulted in a shift in healthcare delivery from that of the hospital to that of the community. Proponents of health care reform are advocating for greater focus on health promotion and the prevention of injury and disease. This, coupled with emerging social and public health issues has resulted in an increasing need for competent and skilled community health nurses.

Unlike the nurse clinician, the role and practice of the community health nurse focuses on promoting, protecting, and preserving the health of populations by working with individuals, families, and communities [1]. Their practice setting, target audience, and the strategies they employ are ever changing, requiring different skills, training, and education. Developing innovative ways to teach these concepts and processes is challenging for nursing educators. Consequently, community health nursing curriculums have predominantly relied on traditional teaching-and-learning approaches where the application and practice of such skills is often quite challenging. Limited clinical placements in community health nursing further intensify the challenges. Virtual learning environments offer a solution to teaching community health nursing education and training.

A *virtual learning environment* can be defined as a self-contained computer based (or internet-based) environment where various tools are provided to enable interactions between the instructor and the student, support teaching, and facilitate the learner's learning experience [2]. Online virtual learning environments including those established on Linden Labs *Second Life*, facilitate distance learners in accessing educational materials. The term virtual learning environment has been used broadly and interchangeably with the terms "educational website", "online learning", and "managed learning environment", amongst others terms. Virtual learning environments provide the opportunity for a learner-centered approach to teaching that is attractive to the current generation of learners, the millennials. Millennial students are technologically literate and see technology as a necessity, both in life and in learning [3]. According to Villeneuve and Macdonald [4], the millennial generation does not remember a time without email, Internet, cell-phones, or lap-top computers and this has shaped the ways in which these students prefer to receive information and how they acquire and retain knowledge. Millenials do not appreciate or learn as much from passive, lecture style learning, but rather, they prefer being actively involved [5]. This high level of interactivity is not easily captured in traditional teaching/learning environments. However, the more recent use of simulations through virtual reality and videogame based technologies have been noted as one of the most effective means of promoting interactivity and active involvement in learning [6].

Recently there has been a push in the use of immersive (3D) virtual learning environments such as virtual simulations, and particularly serious games. A *serious game* can be formally defined as an interactive computer application, that (1) has a challenging goal, (2) is fun to play and/or engaging, (3) incorporates some concept of scoring, and (4) imparts to the user a skill, knowledge, or attitude that can be applied to the real world [7] (see Djaouti et al. [8] for a discussion on the origins of serious games). Serious games have also been more loosely defined as videogames that are used for training, advertising, simulation, or education [9]. Although virtual simulations and serious games are similar and can employ identical technologies (hardware and software), being a videogame, serious games should strive to be fun and should include the primary aspects of games including challenge, risk, reward, and loss. The relationship between serious games, games and simulations is more formally described by Becker and Parker [10] as follows: every serious game (or "simulation game" according to Becker and Parker [10]) is a game, and every game is itself a simulation. As described below, there are a number of benefits associated with the use of serious games for education and training (many of these benefits are equally applicable to virtual simulations). Due in part to these benefits, it has been suggested that serious games provide the potential for a paradigm shift in the delivery of education and training in the twenty-first century [11].

Serious games present a learner-centered educational approach where the player controls their learning environment through interactivity, allowing the player to learn via active, critical learning [12]. They present opportunities for individuals to demonstrate and apply learning, receive immediate feedback on decisions made in realistic learning environments, and are further able to captivate, while engaging students to achieve academic success [13]. Serious games allow users to experience situations that are difficult to achieve in reality due to factors such as cost, time, and safety concerns [14]. Further benefits to learning include: improved self-monitoring, problem recognition and solving, improved short-and long-term memory, increased social skills, transfer of learned skills, use of research skills and increased self-efficacy [15, 16]. Serious games focus on the goals and learning activities of the learner rather than on the presentation of content which is reflective of constructivist theories of learning. The learner is actively constructing knowledge and context of the culture and situations in which they are participating [17]. The constructivist pedagogy typically employed in serious games allow learners to develop personal constructs based on personal observations and interactions; thus, they gain the socialization necessary to make them members of society of which they are studying to become part of [18]. Constructivist theory supports blended learning, providing web-based and face-to-face teaching and learning environments in community health nursing education that are adaptive, highly interactive and meaningful, and learner-centred. However, care must be taken to ensure that blended learning environments consider a number of issues, from the theoretical to the practical, to be effective.

The aim of this chapter is to examine the use of virtual simulation and serious gaming in health care education with a particular emphasis on community health nursing. For clarity, for the remainder of this chapter, unless specified otherwise, the term virtual simulation will encompass serious game. Findings explore both student and educator perceptions regarding the use of gaming as a pedagogical application, how virtual simulations should be integrated into the classroom, assessment techniques, and finally a discussion regarding the need for evaluating learning outcomes associated with virtual simulations in community health nursing is provided.

8.1.1 Review Method

The infancy of nursing informatics and inconsistent definitions within the area of virtual learning environments has resulted in a literature base comprised of disparate studies and commentaries. As a result, an integrative review design was employed. A computerized search using Cochrane Database of Systematic Reviews, CINHAL, Medline (PubMed), Proquest, and OVID was undertaken. Specific strings were developed for each database using a combination of key words, subject headings, abstract, and subject terms such as virtual learning environments* AND health care education* OR nursing education*; virtual simulations* AND nursing* AND education, computer simulation* AND nursing* AND education*, serious games AND nursing* AND education*, serious games*, virtual reality* AND nursing* AND education*. This strategy ensured the comprehensive identification of papers, helping to mitigate potential limitations caused by inconsistencies in the indexing of review topics [19]. In addition, the reference lists of those papers identified for inclusion formed the basis for a hand search to identify further potentially relevant literature. Peer reviewed journal articles with primary quantitative studies such as those with quasi experimental or similar design, any qualitative research design, literature review, or theoretical framework written in the English language only, published from January 2000 to April 2013, were included.

The search strategy identified 368 abstracts for review. Based on the inclusion criteria, and after eliminating overlaps and screening of titles, abstracts, and key words, 10 publications were retained for review: one framework report, and nine empirical studies. After examining the reference lists of all included publications, two additional empirical studies were included. Twelve articles were finally identified and included in this review.

Quality checks were performed on all of the included empirical studies, first selecting the abstracts for inclusion and completing the initial review. The second review involved quality checks using an assessment tool offered by the *Effective Public Health Practice Project* [20] (see Thomas et al. [21] for greater details). A four-stage systematic analytic method making use of qualitative approaches was then employed. First, a standard format for summarizing descriptive and methodological information and outcomes of included studies was developed. The recorded dimensions included: descriptive information (author, date of publication, and methodology); description of study objectives (focus, target audience); and definitions offered; and any findings and opinions related to gaming as an educational tool intended to enable the design, implementation and evaluation of simulations by healthcare educators. The extracted information was compared and patterns recorded as they became apparent. The results of the comparative analysis were further analyzed, from which it was possible to discern groupings of similar data and identify themes. Four key themes were identified at this stage and will be discussed further in the remainder of this chapter. Quality checks of the framework was completed using Chinn and Kramer's [22] guide for theory/model analysis, exploring clarity, simplicity, generality, empirical precision, and deliverable consequences.

8.2 Perceptions of Games in Learning

Traditional teaching-and-learning environments do not meet the unique learning needs of millennial students and are often quoted as boring. Two quantitative studies found that almost half of the respondents reported playing games and that students support the use of new media technologies in education [23, 24]. Respondents in each study indicated that strategy/simulation games were amongst the top three genres most often played [23, 24] and approximately half of the respondents (52 %) were interested in using multiplayer online health care simulations that would realistically replicate the experience of being in professional practice [24]. Kapralos et al. [23] found more than three quarters of the respondents have used virtual simulations in the past and indicated that they found them useful and aided in grasping course theory. In a Midwestern United States university, pilot testing with nursing students using a "virtual simulation game" revealed that students were very enthusiastic about the experience and provided suggestions for expanding the game [25].

A study examining the use of a virtual community known as *The Neighbourhood* reported students seeing relationships between course concepts and The Neighbourhood [26]. A qualitative survey completed by students using The Neighbourhood reported positive benefits to learning when assignments or in-class learning activities incorporated characters or situations from the virtual community. Comments also suggested that the degree of integration between The Neighbourhood and class work was a key factor in their perceived benefits [27]. Continued use of The Neighbourhood characters and situations gave life to concepts and content as students were able to link them to clinical applications [27]. The frequency of virtual community use in nursing education appears to be linked to positive learning benefits and engagement [28]. In Schmidt and Stewart's [29] evaluation of Linden Lab's Second Life, students reported that they liked the ability to meet with other students in real time and receive feedback, and they also appreciated the opportunity to meet the instructor in Second Life to clarify material or discuss course concerns [30].

Faculty appear reluctant to apply a pedagogical tool that has received limited research regarding pedagogical implications, and learning outcomes. In a survey conducted by Kapralos et al. [23], 50 % of faculty participants indicated that they have used virtual simulations, and 72 % answered that they added value to their course. Of those who did not use them, 50 % responded that they did not use them due to a lack of availability. In addition, 66 % stated they would fully integrate a simulation were it available to them, yet 22 % said they would allow students to "play around with them as an extracurricular tool, but would not use it as a part of course evaluation". Although a large number of faculty are willing to integrate a virtual simulation into their curriculum, there are still those that are reluctant to do so. This reluctance may be due to a number of factors including lack of prior knowledge and experience with virtual simulation and game-based learning, and the fact that such technologies in the past, particularly during the *Edutainment* era, have not lived up to their expectations and the resulting resentment still remains today (see Becker and Parker [10] for greater details regarding the Edutainment era).

Millennial students have not lived without technology thus it is not surprising that they regard the experiential learning offered by virtual simulation a necessity for their learning success. Previous findings suggest that students and educators appreciate the use of virtual simulations but care must be taken to ensure that they are relevant to the course material, that educators have access to them and are familiar with their use to assist students should problems and questions arise.

8.3 Designing and Integrating Virtual Simulations into the Nursing Curriculum

Nursing education is calling for innovative strategies and integrative teaching to build a body of evidence that will guide the practice of teachers. Integration into the course or curriculum is vital to success. However, successful integration and learning from the use of virtual simulations requires proper design. There is a need for a consistent and empirically supported model to guide the design and implementation of virtual simulations and to assess outcomes. Jeffries [31] offers a theory-based framework that proposes a four step process to simulation development. Step one: involves working from a conceptual framework that specifies variables and relationships that promote understanding of the processes involved in developing, implementing, and evaluating simulations in nursing education. Step two: relates to the materials needed for the setup, such as, simulation set-up, staffing, and guided reflection time. Step three: refers to four major components in the structure: (1) the teacher's role, (2) the student's role, (3) the process of embedding educational practices into the simulation, and (4) the timing of the simulation itself. The teacher's role refers to the essential need of teachers to the success of alternative learning experiences. When virtual simulations are employed, teachers work as facilitators and it is therefore crucial that they feel comfortable with the virtual environment itself and are prepared to assist students with any questions and problems they may have. Specific roles are assigned to the learner during the simulation and therefore students must have specific information related to their assigned roles, and learning needs should be evaluated related to progress in attaining learning outcomes. Jeffries [31] refers to four principles of good educational practices that are identified as important to learning: (1) active learning, (2) collaboration, (3) diverse ways of learning, and (4) high expectations. When developing a virtual simulation, the amount of time needed to accomplish the objectives also requires consideration. Simulations (physical or virtual) should be timed with student instruction and instrumental to the timing of the simulation is the time provided for guided reflection. The fourth and final step in the four step process includes evaluation, which is needed to assess the learning outcomes as well as the overall process of design and implementation.

The Federation of American Scientists held a summit on harnessing the power of videogames for learning in October 2005 [32]. Among the groups recommendations was a list of 10 attributes of games for application learning (although not specific to nursing education, these attributes are applicable to learning in general):

1. Clear learning goals.
2. Broad experiences and practice opportunities that continue to challenge the learner and reinforce expertise.
3. Continuous monitoring of progress, and use of this information to diagnose performance and adjust instruction to the learner's level of mastery.
4. Encouragement of inquiry and questions, and response with answers that are appropriate to the learner and context.
5. Contextual bridging: closing the gap between what is learned and its use.
6. Time spent on task.
7. Motivation and strong goal orientation.
8. Scaffolding: providing learners with cues, prompts, hints, and partial solutions to keep them progressing through learning, until they are capable of directing and controlling their own path.
9. Personalization: tailoring learning to the individual.
10. Infinite patience.

Other authors concur with many of Jeffries' [31] four steps and the Federation of American Scientists' [32] recommendations. For example, Susi et al. [9] cautioned that the individuals playing educational videogames (within an educational setting) may not necessarily be seasoned gamers, therefore game set-up should ensure accessibility. Shuster et al. [27] found that students appreciated when the simulation coincided with course concepts. Schmidt and Stewart [30] learned that students and faculty need to be adequately prepared with an orientation session before or at the start of the semester, not in the middle of an already stressful program. It was also suggested that a designated staff member should help both students and faculty with technical problems or training needs [29, 30]. Students using Second Life identified the need for clear expectations and explanations in advance of the implementation and overall the authors suggested that there is a need for clinical faculty to encourage students to use the activities [30]. Honey et al. [33] stressed the importance of planning and adequate preparation to ensure a focus on learning and the need for orientation. Finally, Kapralos et al. [23] noted that the virtual simulation must feel as though it is being linked to the course material; the simulation must be user friendly; and the faculty/educators must integrate the simulation into their course material through understanding and competency with the application. Many of the empirical studies also made reference to the need for additional research on assessment and learning outcomes related to virtual simulation.

A simulation framework that specifies relevant variables and their relationships is needed to design, implement, and conduct research in an organized, systematic fashion ensuring learning outcomes are adequately evaluated.

8.4 Assessment of Student Learning

Assessment and testing is crucial in determining whether the student has understood the material and is able to recall and use the material appropriately. Therefore, virtual simulations, just like every other tool of education, must be able to show that the necessary learning has occurred and must provide some means of testing and progress tracking which is recognizable within the context of the education or training they are attempting to impart [15]. One of the main disadvantages with present virtual simulations is the lack of research validating outcomes. That being said, learning is a complex construct making it difficult to measure and determine whether a simulation has achieved the intended learning goals or has had the desired effect [34–36]. Commentaries suggest that consideration must be given to the pedagogy adopted (e.g., *problem-based learning*) as this will guide assessment. For example, with respect to a serious game, the game can monitor activities, and outputs, and the game characters can probe student behaviour in the course of their interactions. Once the game has determined the status of the student's proficiency, it can make decisions on how to evolve the scenarios to embody more challenging learning objectives or to offer various forms of remediation [37].

Virtual simulation involves less emphasis on rote memorization of facts and therefore assessment data obtained from traditional methods may not accurately reflect the learning gained from serious games. With respect to serious games, Michael and Chen [15] suggest that there are three main types of assessments: (1) completion assessment, (2) in-process assessment, and (3) teacher evaluation. Completion assessment simply asks, "Did the student complete the serious game". Serious games involve interaction by the students with the material, thus completing the game could signify more learning progress and comprehension than passively attending lectures [15]. In-process assessment is analogous to teacher observations of the student. The game (or virtual simulation) offers logging potential and may track such items as: time required to complete the lesson, number of mistakes made, number of self-corrections made, amongst others [15]. Multiplayer games often include *observer modes* which offer the teacher an opportunity to observe the student in action. Teacher evaluation is a combination of both completion assessment and in-process assessment (a thorough overview of serious games assessment is provided by Bellotti et al. [38]). Hogan et al. [39] describe a serious game for community health nursing and suggest that scenarios in the game be structured around rigid protocol scripts that require adherence to time-or sequence sensitive action protocols, or they can be unstructured, requiring satisfactory real-time response to emerging events and information. Student responses can take the form of immediate, direct action in real-time, or the issuance of recommendations for further action by a third party. Instructors may use in-process assessment to evaluate student's success, thereby allowing the educator to provide the student with feedback and generate a grade [39].

Assessing the learning within a virtual simulation is not a trivial matter and further research is required. Serious games (and games in general) can and generally do contain in-game tests of effectiveness. More specifically, as players progress through the game, they accumulate points and experience which make the next stages and levels of the game easier and thus should score higher if any learning has been imparted [10]. Recent work is focusing on the use of such *in-game assessment* as it takes us away from the predominant, classic form of assessment comprised of questionnaires, questions and answers, etc. These classic forms of assessment do nothing more than test our memory rather than measure an understanding and/or creative use of the acquired knowledge which can interrupt and negatively affect the learning process [40]. In-game assessment provides the opportunity to take advantage of the medium itself and employ alternative, less intrusive, and less obvious forms of assessment which could (and should) become a game element itself [40]. Integrating the assessment such that the player is unaware of it forms the basis of what Shute et al. [13] describe as stealth assessment and this represents a new and growing area.

8.5 Evaluation of Learning Outcomes

Numerous benefits of virtual simulation have been espoused however little research has been completed on actual learning outcomes. Farra et al. [41] recruited second year students from an associate degree nursing program at a community college. The aim of the study was to examine the effects of a virtual simulation on learning outcomes and retention of disaster training with nursing students. Participants were randomly assigned into two groups; both groups completed web-based modules; the treatment group also completed a virtually simulated disaster experience in Second Life. Analysis of the overall model was statistically significant ($p < 0.0001$) indicating that there were significant differences between the virtual simulation (treatment) and non-simulation (control) groups. The two month post-knowledge assessment demonstrated that virtual simulation had a strong positive effect on retention of disaster training [41]. Similarly, a study evaluating the effectiveness of a serious game in teaching major incident triage by comparing it with traditional training methods found that compared to the traditional method, those who underwent the serious game training performed higher on tagging accuracy (assigning correct triage tag to the causality [42]). Step accuracy (following correct procedures) was also higher in the game group. A recent study by Cook et al. [43], which examined reviews of the medical simulation literature, has shown that technology-enhanced simulation, in comparison with no intervention (i.e., no simulation), is associated with large positive training effects. However, the relative merits of different simulation interventions remain unknown.

Given the lack of research in the area of virtual simulation for community health nursing, the scope was expanded to learning outcomes in all virtual simulations used for healthcare education. In a quasi-experimental study conducted to determine the effectiveness of supplemental gaming on students' comprehensive knowledge of pediatric cardiovascular dysfunction, with no significant differences in the pre-test, the experimental group (lecture and game) scored significantly higher than the control group on the post-test [6].

In another novel study, instructional videos were developed to facilitate medical students' understanding of how to perform an effective home visit [44] in a videogame environment. In this videogame, students were expected to navigate the home of an elderly person. In doing so, the student had the opportunity to identify any risk factors they assessed. They clicked on the risk factor, and if correct, they scored points; there was a total of 50 risk factors. Once entering the elderly person's home, the player had a total of 10 minutes to identify the risk factors. After completing the game, the student was directed to a summary page that highlighted the correct risk factors in each room and included referenced feedback. Medical students were required to use the game during a 4-week geriatric rotation. Students using the game during a 4-week geriatric rotation demonstrated statistically significant improvement from pre-test to post-test [44]. These results support the use of instructional videos as a beneficial tool for learning home risk factors for the elderly.

From the scant literature, it appears gaming does have a positive effect on student learning outcomes (as shown in [44] and as shown in various other studies too including those described in [7, 45, 46]). However, as noted by Jeffries [31], outcome measures such as knowledge, skill performance, selfconfidence, learner satisfaction, and critical thinking related to the use of gaming (serious games) in healthcare education requires further research.

8.6 Discussion

This review focused on the use of virtual learning environments in the form of virtual simulation and serious gaming in health care education with emphasis on community health nursing. Research demonstrates that students do play and enjoy videogames, have positive attitudes toward virtual simulation and recognize that new media technology could facilitate and strengthen nursing education. Students prefer to have any virtual learning environment used within the course curriculum linked to classroom concepts and increased perceived benefit with continued increased use of the application was noted. When provided the option, students consistently chose to continue with the application and offered recommendations related to orientation, additional scenarios, and feedback on student performance.

Although health care educators recognize the value of virtual simulation, additional research regarding their use as sound pedagogical applications is required to support uptake of this innovative strategy, particularly with respect to the integration into the classroom, assessment, and learning outcomes is needed. Endorsement will also be enhanced with faculty orientation and support as this is a new application for many educators.

This review demonstrates that virtual simulation provides nursing students the opportunity to experience and analyze system influences on personal and patient safety, enabling them to practice skills without harming patients. Virtual simulation ties into constructivist pedagogy by offering opportunities for first-person, experiential learning and reflection. Students gain knowledge and experience through interaction with the concepts and constructs in the simulation, reflecting on their learning through blog posts and discussion threads, which helps construct their learning. Recently, there has been a growing interest in the use of serious games but despite their popularity, there are many examples of ineffective of serious games that is, serious games that provide little, if any, educational value. This is often attributed to the fact that these they lack appropriate instructional design [35, 47]. To develop effective serious games (and virtual simulations in general), care must be taken to ensure that they are properly designed to meet their intended goals [10, 48]. In other words, designers and developers cannot ignore the importance of instructional design.

Best practice for developing simulations in general involves the use of a framework that guides the design, implementation and suggests variables for evaluation. Integration of the game into the curriculum is integral to the educator's success. If it is viewed as an add-on or additional experience the value of the technology will be lost.

The lack of research regarding learning outcomes that can be achieved and the cost of production are barriers to the design and development of virtual simulations by educational institutions. However, as a didactic medium, virtual simulation provides the opportunity for applying learned theory in a life-like clinical environment and assists in developing skills required for community health nursing practice and should not be ignored. Future recommendations include the need for interdisciplinary collaboration in the development of a virtual simulation. Specialists with programming skills and technology system design will need to work closely with educators and nurses' with knowledge of the subject matter to ensure good pedagogy is incorporated. There is also the need for high-quality research on assessment strategies and learning outcomes of simulations.

With respect to health professions education, Cook et al. [43] conducted a study that involved a thorough literature review and synthesis of the existing evidence in educational science to determine the instructional design features that lead to improved outcomes in studies that directly compared one technology-enhanced simulation training approach to another. Although they highlight the need for further research, Cook et al. [43] suggest 12 essential features and hypothesized that outcomes would increase with an increase of each feature. The 12 essential features are: (1) clinical variation, (2) cognitive interactivity, (3) curriculum integration, (4) distributed practice, (5) feedback, (6) group versus independent practice, (7) individualized learning, (8) mastery learning, (9) multiple learning strategies, (10) range of task difficulty, (11) repetitive practice, and (12) time spent learning.

8.6.1 Limitations and Future Work

As an emerging application in healthcare education there is little research regarding the use of and effectiveness of virtual simulation. The evidence available is limited to descriptive and comparative commentaries that focus on the implementation and development of virtual simulations and little on learning outcomes. Available evidence is limited to single-site studies with small sample sizes and relies on self-report and interview methods to obtain data. The lack of homogeneity among the research available make it challenging to make comparisons with the findings.

Future research needs to focus on better explaining the engaging aspects of serious games, and if there is a need for practical guidance regarding how (when, with whom, and under what conditions) to integrate games and learning processes to maximize their learning potential [9]. Process evaluation of game design and additional high-quality large scale evaluations exploring the impact of educational games on patient and performance outcomes is needed. Lastly, there is also a need for research evaluating virtual simulation as an assessment method.

8.7 Conclusions

Community health nurses require different knowledge and skill sets than those of their nurse clinician counterpart. Despite the current studies focusing on one-to-one patient interaction or didactic skill, we find that the research on virtual simulation also suggests benefit to community health nursing education. Virtual simulation offers alternatives to the current lack of clinical placements and the incorporation of new technology addresses the different training required by community health nurses. The use of new technology in education also reflects the direction of nursing education, which includes more interactive learning, student-centered approaches, and increased opportunities to experience realistic scenarios, and simulations of clinical practice to promote problem-solving and decision-making skills. As new methods are incorporated into the teaching-learning process, nurse educators will have to be mindful of the need for educational research testing of learning outcomes.

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Chapter 9
Facilitating Learning Through Virtual Reality Simulation: Welcome to Nightingale Isle

Jone M. Tiffany and Barbara A. Hoglund

Abstract The profession of nursing is at a pivotal point in terms of technology, complexity, and pace of change, placing increased stress on the field of nursing education. The challenge for nursing faculty is to find the time, energy, skills, and resources to assimilate innovative strategies such as real life and virtual simulations, and role-playing into routine teaching/learning activities. This chapter will present an overview of Nightingale Isle, a collaborative learning space that is part of the 3D virtual world of Second Life™. This virtual learning space was designed around the theme of Florence Nightingale, one of the founders of the nursing profession, and was initially created to encourage, challenge, and support nursing students in their journey to become nurses, and is expanding to include interprofessional learning activities. The virtual space known as Nightingale Isle includes classrooms, an education building, a library, an outdoor presentation area, clinic, hospital, and neighborhood. This chapter will include a discussion of a variety of virtual reality simulation (VRS) student learning activities taking place on Nightingale Isle, such as medical simulations, ambulatory care role-play experiences, virtual lectures, and public health clinical assignments. Results of selected VRS projects are presented. The chapter will also introduce the Virtual Reality Simulation Educational Model, a framework based on constructivism that is useful for guiding the development and use of simulated learning activities within virtual reality settings.

9.1 Introduction/Overview

Simulated learning experiences have become well-integrated into nursing education since the introduction of high-fidelity human patient simulators by Laerdal in 2000 and METI in 2001 [15]. Simulations provide a means to facilitate active

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learning in an environment that promotes safety and quality. According to Nehring [13], virtual reality simulations are the next era of simulation to be used by nurse educators to teach and evaluate nursing students and nursing skills. In fact, the current generation of nursing students has grown up with technology and desires active learning experiences such as those that occur in the virtual world [13].

There are multiple increasing complexities in healthcare related to factors such as technology, ethics, public policy, economics, and system changes that must be addressed in the educational setting. Together, these contextual factors have required an emphasis on safety and quality in nursing education. As a result, reliance on traditional teaching/learning pedagogies limits the ability of nurse educators to effectively teach and promote safety and quality. Devane and Bauman [5] identify significant pedagogical concerns related to traditional didactic instruction:

> While nurses entering into clinical practice are not expected to be experts, one might expect that nursing students would have a substantive amount of clinical experience. Instead, nursing students are presented with hours of verbal instruction about what they should do in often-critical situations. Didactic verbal instruction about the critically important activities of nursing practice does a disservice to nursing students, leaving them with little real-world experience on which to draw (p. 51).

Instead, nurse educators need to design context-rich learning experiences that enhance and transform learning in ways that allow the learner to "try out acquired skills and discover new ones in a controlled environment" [5, p. 50].

When used effectively, virtual reality simulations allow educators to incorporate salient contextual data, environmental factors, and safety and quality issues directly into teaching/learning activities in order to create more realistic learning opportunities (see Fig. 9.1). Learners are able to develop clinical expertise in carefully designed, meaningful, and relevant simulations that expose them to the complexities of authentic nursing practice. However, use of virtual simulations poses a challenge for nurse educators. It takes significant time, energy, skills, and resources for educators to become familiar enough with virtual reality software in order to successfully incorporate virtual simulations into routine teaching/learning activities that can be used across nursing curricula.

9.1.1 The Virtual World of Second Life™

Second Life™ (SL) was created in 2003 as a "Massively Multiplayer Virtual World" social networking and gaming platform by Linden Labs. SL participants are offered a 3D immersive virtual world experience via an internet connection and free downloadable software. Virtual world experiences replicate real world activities such as lectures presented with PowerPoint™, professional seminars, theatre and museum visits, and continuing education sessions as well as numerous opportunities for socialization and recreational activities. Avatars are used in SL to facilitate participation in virtual world activities.

Fig. 9.1 Dr. Tiffany, nurse educator, facilitating a VRS on Nightingale Isle (Used with permission)

9.2 Nightingale Isle

Nightingale Isle is a virtual, collaborative, and interactive learning space within the 3D online virtual world of SL Originally created in 2010 by Dr. Jone Tiffany, Nightingale Isle has multiple learning spaces designed to facilitate, encourage, challenge, and support nursing students in their journeys to become nurses (Fig. 9.1). It is a virtual environment uniquely designed around the theme of Florence Nightingale, one of the founders of the nursing profession. While the current focus of learning activities is on nursing education, future activities using Nightingale Isle will be designed to foster collaborative and experiential interprofessional education learning activities.

This chapter describes the various learning spaces within Nightingale Isle, an overview of teaching/learning strategies used, indicators of student learning while using virtual reality technology, a discussion of the constructivist framework that supports teaching/learning in virtual reality simulations, and plans for future teaching/learning activities. Furthermore, the Virtual Reality Simulation (VRS) Educational Model [19] will be introduced.

Nightingale Isle has multiple spaces available for teaching/learning. To date, the isle includes: Nightingale Hospital; South Street Clinic which includes a family medicine clinic on the ground floor and the isle's public health department

Fig. 9.2 *Crimean Classroom Center* Outdoor classrooms with presentation podiums and interactive internet-based presentation screens. These spaces can be used for a variety of learning activities or lectures (Used with permission)

on the second floor; The Blackwell Conference Center, named after Elizabeth Blackwell, a physician friend of Florence Nightingale; Crimean Classroom Center (Fig. 9.2); Our Lady of the Lamp Library; Compassion Commons (Fig. 9.3); Ministering Angels Healing Place, a gazebo that can be used as a social or formal meeting place; and a park area for recreation and relaxation. Future spaces include several neighborhoods where families live in urban, suburban, and rural environments to facilitate community, public health and clinical reasoning learning activities.

9.2.1 Nightingale Hospital

The hospital (Fig. 9.4) was designed and developed to be used for patient simulation scenarios that include clinical decision-making, delegation, and collaboration components that promote clinical reasoning and competence. The space includes an emergency department (ED) consisting of six patient emergency "bays," a triage area, and two private examination rooms used for triage and treatment

Fig. 9.3 *Compassion Commons* An outdoor presentation area and gathering space used for lectures and meetings (Used with permission)

Fig. 9.4 Nightingale Hospital (Used with permission)

scenarios. In addition, there is a conference room, a mental health seclusion room, two classroom/debriefing rooms, and a second floor multi-use staging/rezzing area that is used for a variety of medical simulation activities.

The conference room has a virtual, interactive screen where actual videos and PowerPoint™ lectures can be viewed. This room is used for care conferences, prebriefs, and debriefing sessions. In addition, there are classrooms available for lecture. These rooms can be modified to accommodate other learning activities such as role-playing giving bad news to families; teamwork, communication, and collaboration scenarios; and practice calling providers to report an incident or obtain orders. Currently, these roles are played by standardized patient avatars or delivered via scripted notecards. Future development includes the use of interactive artificial intelligence robots (bots) that can be programmed to answer questions and interact with students.

The second floor of Nightingale Hospital is developed so that faculty can choose from a variety of clinical settings in order to run various simulation scenarios that allow for scaffolding of learning activities. For example, one of the choices is a comprehensive and scaffolded obstetrics simulation that includes use of a labor and delivery room, a surgical suite, a newborn nursery, and a postpartum area. One learning activity designed for the obstetrics simulation space is a case study portraying a pregnant woman who presents to the ED in labor after being in a car accident, is transferred to the labor and delivery area, develops issues with the fetus, and is transferred to the OR for a Cesarean birth.

9.2.1.1 Simulation Research and Learning Activities in Nightingale Hospital

The emergency department of Nightingale Hospital is the setting where the first author's National League for Nursing (NLN) Health Information Technology Scholar (HITS) project took place. The HITS project consisted of a pilot simulation using the Henry and Ertha Williams unfolding case study associated with the NLN's Advancing Care Excellence for Seniors (ACES) initiative [14]. Within one of the private rooms, there is a hospital bed for Henry with Ertha (Fig. 9.5) sitting nearby, as well as equipment commonly found in a patient care area including a cardiac monitor, Pyxis machine, IV pump and a computer connected to the internet for charting.

A convenience sample of ten senior nursing students participated in a pilot simulation project. The pilot began with a face to face orientation to SL; continued with a virtual lecture held in the Blackwell Conference Center covering information about health alterations in the older adult, including an introduction to the Fulmer SPICES tool [7], followed by an orientation to the simulation environment within Nightingale Hospital. Upon completion of the orientation activities, the students participated in the simulation using part one of the Henry and Ertha NLN ACES unfolding case study. After the scenario was finished, a forty-minute virtual debriefing session was held in the Nightingale Hospital conference room. The participants then took an anonymous survey to evaluate the experience of participating in a simulation in the virtual world of SL. Overall, participants found the virtual reality simulation (VRS) to be a positive experience. However, there were multiple comments about the short orientation, and they desired more time

Fig. 9.5 Henry and Ertha in a room at Nightingale Hospital within the VRS (Used with permission)

to explore and learn how to move and control their avatars in SL. Most students indicated they would have preferred a separate orientation to SL with ample time to practice moving around, changing clothes, and learning how to click on various objects in order to more easily participate in the VRS within Nightingale Isle. On the positive side, several students commented about feeling as if they were actually present in the virtual learning space, felt connected to one another, and enjoyed this particular learning environment. This initial student feedback was very helpful in the design of future VRSs.

Future VRSs within Nightingale Hospital include a senior (fourth year) capstone clinical decision making/delegation simulation. Each student will independently assess six patients and make decisions about priorities for care. At the end of the simulation, the students will be debriefed in their clinical groups—discussing the rationale for specific decisions of care and delegation.

9.2.2 South Street Clinic

The South Street Clinic (Fig. 9.6) was designed for VRS activities for two separate nursing courses; one in the traditional baccalaureate nursing program, and one

Fig. 9.6 South Street Clinic (Used with permission)

in the baccalaureate nursing degree completion program. The South Street Clinic consists of two floors: the first floor houses the Family Medicine Clinic and the second floor, the Public Health Department.

The family medicine clinic has multiple examination rooms used for a variety of learning activities, such as role-playing, simulated patient visits, patient interviews, and assessments. The rooms are set up with an exam table, two chairs, a sink, and a computer linked to the internet so students can chart their findings. Two of the exam rooms are attached to conference rooms with interactive presentation boards (Fig. 9.7). The family medicine clinic was the setting for the junior (third-year) student clinical reasoning assignment. All students in the course participated in one VRS clinical replacement day at some point during the semester. In the VRS, students cared for four ambulatory care clients visiting the Family Medicine Clinic for diabetes care. The clients were from a variety of ethnic backgrounds and ranged in age from 21 to 83 years. In addition to diabetes, each client had a co-morbidity of anxiety or depression, and one client also had heart failure. After the students individually interviewed/gathered data from each client and answered several guided reflection questions, they developed a complex concept map for each patient and attended an hour-long face-to-face debriefing session with the instructor. Preliminary data show that students found these learning activities meaningful and helpful, while providing an opportunity for them to practice interviewing, assessing, and caring for clients with clinical conditions and associated factors they otherwise may not have had an opportunity to encounter.

The Public Health Department on the second floor of the South Street Clinic has two private offices for meetings with clients or virtual office hours for faculty-student appointments. This space is configured for five different public/community health VRS assignment scenarios that consist of one learning module in the course. The five scenarios include:

Fig. 9.7 Family Medicine Clinic conference room (Used with permission)

1. A single mother who has an appointment in the Women with Infants and Children (WIC) clinic
2. A postpartum assessment of a woman who has postpartum depression
3. A family with three children, one of whom was just diagnosed with diabetes, visits the family health clinic
4. A pregnant teen and her boyfriend visit the adolescent health clinic in the public health department for health teaching
5. An interprofessional care conference discussing a child with a new diagnosis of autism

9.3 Theoretical Framework Supporting VRS: Constructivism

It is important that virtual reality learning experiences are supported by a theoretical framework that guides the development, implementation, and evaluation of teaching/learning strategies. Constructivism is often used to support teaching/learning in online and virtual environments [6, 8, 11]. In constructivism, the focus is on facilitation of student learning; the instructor is a colleague and partner in the learning process. From a constructivist lens, the role of the educator resides not with delivering information, but with facilitating learning aimed at understanding the nature of how this learning happens [12]. The process of facilitation can be uncomfortable for some traditional educators, as they may have drawn satisfaction from being the expert who covers all the content in class. Another tenet of constructivism is the notion of active learning—learning by doing. Active learning is noted to be one of the preferred types of learning for adults [3].

In the literature, there are numerous examples of the application of constructivist learning principles in nursing education. It is evident that nursing students who engage in active learning exhibit higher-order thinking skills and are able to construct new meaning out of what is taught in the nursing curriculum [1, 9, 10, 12, 16, 18]. As the educator makes the shift from teaching knowledge to facilitating learning, relationships, communication, and social interaction become very important parts of the process.

Furthermore, constructivism expects the student to build upon previous learning in order to build new knowledge. The constructivist framework also requires opportunities for self-reflection on learning and the learning process [17].

9.3.1 Scaffolding

The teaching/learning approach called "scaffolding" is important in VRS. Vygotsky [20] defined scaffolding instruction as the "role of teachers and others in supporting the learner's development and providing support structures to get to that next stage or level" (p. 126). An important aspect of scaffolding instruction is that any given scaffold (i.e., structured support) is temporary. As the learner's abilities increase, the scaffolding provided by the instructor, or fellow student, is progressively decreased or withdrawn and new scaffolding instruction is offered if appropriate to advancing learning even further. Eventually, the learner is able to complete the task or master the concepts independently [4].

Research on the role of scaffolding in education has revealed that providing support to students can help learners improve their learning both in the cognitive and affective domains. Through faculty use of scaffolding strategies, learners are able to spend more time learning and less time worrying about the technology. The learning strategy of scaffolding is an important concept when considering introducing new types of technology to nursing students or healthcare professionals in the practice setting. The more support available to the learners, the less anxiety, the higher the self-efficacy, and the higher the retention of the knowledge taught [2].

9.4 The Virtual Reality Simulation Educational Model: Using a Constructivist Framework to Enhance Clinical Reasoning

In order to assist faculty in developing relevant VRS experiences, the Virtual Reality Simulation Educational Model [19] is proposed (Fig. 9.8). Principles of constructivism provide the foundation for the VRS Educational Model and guide the design,

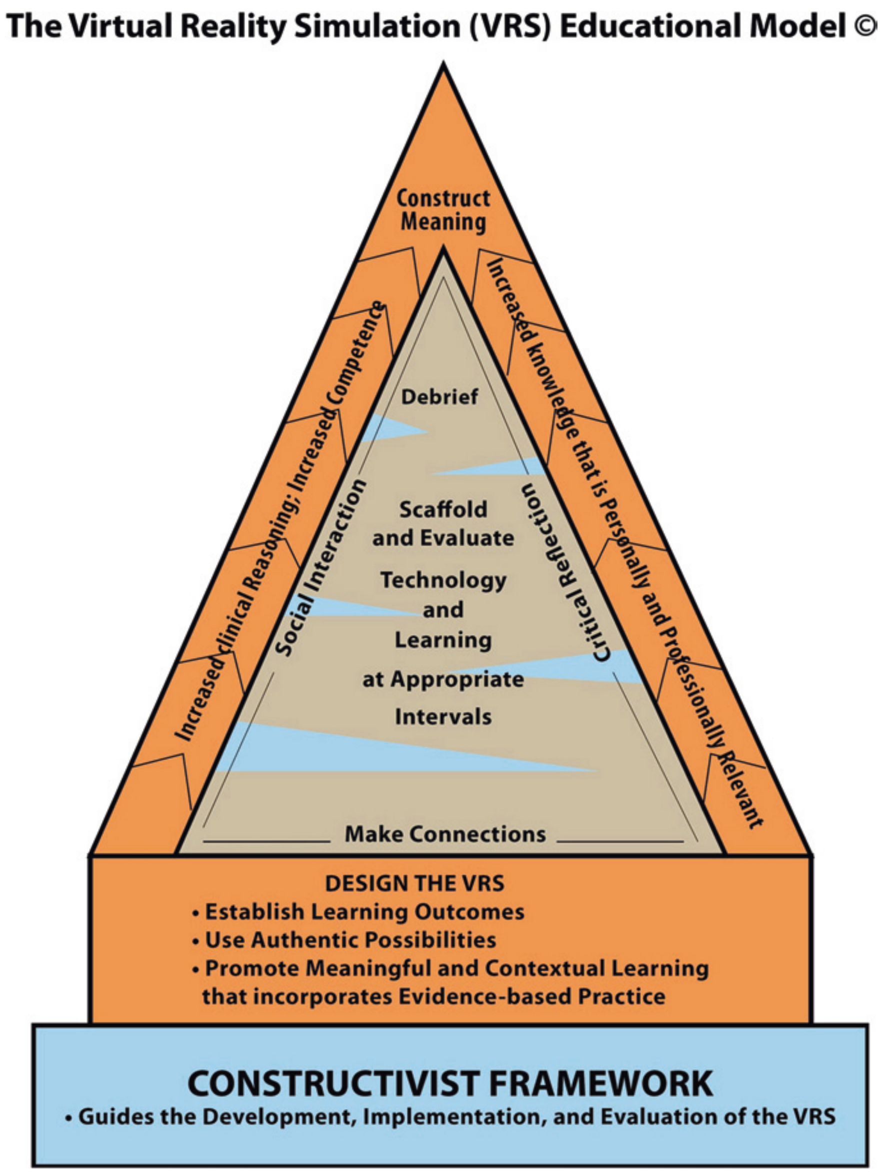

Fig. 9.8 *Source* Tiffany and Hoglund [19] (Used with permission)

implementation, and evaluation of the entire learning experience in order to "generate increased clinical reasoning skills, increased clinical competency, and increased knowledge that is personally and professionally relevant" [19]. Throughout the implementation of the learning experience, the VRS Educational Model addresses scaffolding needs related to technology used throughout the learning experience and in regard to the complexity of the clinical scenario. The presence of the nurse educator (synchronous or asynchronous as appropriate to the simulation) allows for individualization of scaffolding strategies that address technological and clinical learning needs at appropriate intervals throughout the simulation. At the same time, the VRS Educational Model embeds social interaction and collaboration throughout the learning experience in order to make connections and to facilitate critical reflection on learning [19]. At the close of the VRS exercise, the model includes debriefing as the final step toward construction of meaning that is reflective and transferable to the practice setting.

9.5 Using the Virtual Reality Simulation Educational Model: Public Health VRS

Because the quality of student learning varied according to the setting and the preceptor, faculty desired a more standardized learning experience to ensure that application of core public health principles was experienced by all students. The VRS example presented here describes three learning modules designed for a public health course in a BSN degree completion program for RNs at a private Christian university in the midwest region of the United States. The setting for this VRS is Nightingale Isle's Public Health Department located on the second floor of the South Street Clinic. Selected faculty observations, student characteristics, and student responses are included to enhance understanding of how VRS has been used in nursing education.

The following learning outcomes for the modules were established:

1. Integrate an understanding of population-focused principles, family theory, disaster planning/emergency preparedness, and the Christian worldview in the care of clients in the community.
2. Critically analyze health disparities, barriers to adequate healthcare, and community assets/resources for improving health quality from an ethical perspective.
3. Evaluate evidence-based public health nursing interventions to address health disparities in a given population, emphasizing the roles of advocate and collaborator.
4. Identify the incidence and/or prevalence, distribution, and control of disease in a population as well as the protective factors, risk factors and environmental factors related to communities.
5. Demonstrate effective verbal, electronic, and written communication skills.

Three standardized VRS learning modules were developed to facilitate interactive, experiential learning. All students worked through the same scenarios during the learning process.

Module 1: Five VRS scenarios that are linked to family theory didactic content. Each scenario reflects complex real world issues such as teen pregnancy, loss of job, alcoholism, depression, poor access to services or healthcare. (Figure 9.9)

Module 2: Plane crash VRS scenario that is linked to disaster planning and emergency preparedness training didactic content.

Fig. 9.9 *Family Health Clinic* Nursing student working with family and child with new diabetes diagnosis (Used with permission)

Module 3: Home safety assessment VRS with the purpose of simulating the role of the public health nurse completing a home safety assessment. The module requires collaboration with a group of student peers to determine safety priorities and develop a list of actions that must be taken before an elderly homeowner can return to her home.

9.5.1 Implementation of the VRS

Since these students had not used SL before, the VRS began with a two hour face-to-face orientation in order to be able offer adequate technology and content scaffolding. The VRS modules were developed to be completed in an asynchronous manner following the face-to-face orientation. Although several of the activities could have been completed via group learning in the simulated spaces, they were designed to be asynchronous to allow the students to complete the simulations within their own time frames.

After completing each module of the Public Health VRS, the students individually debriefed by answering guided reflection questions. They were then randomly assigned to online discussion forums and asked to discuss one of the VRS scenarios. The online discussion activities afforded the students an opportunity for both self-reflection and reflective dialogue within their group. In addition, each group was tasked with developing a nursing diagnosis, plan of care, and referral plan for patients in their designated VRS scenario.

As previously noted, the students in this exemplar were adult learners enrolled in a baccalaureate degree completion program Public Health course. None of the students had any prior exposure to virtual reality, and several stated they struggled with technology in general. The students were varied in their computer self-efficacy and technical abilities. Several students needed one-to-one assistance and support from the instructor which was provided using the principles of scaffolding. Others had a few questions prior to gaining confidence and independence. A small number of students were very independent from the beginning and needed no additional assistance after the orientation session.

Each time the students began a subsequent VRS module, it was observed that it was easier for them to navigate the software. For the second module, a couple of students needed minor assistance with the technology but the majority of students were very independent. By the third and final module, student questions were limited to assignment clarification and were devoid of concerns regarding technology.

The nursing practice experience among this group of students ranged from 1 to 30 years of nursing experience. With this in mind, the clinical complexity of the VRS modules were designed to challenge potential assumptions and stereotypes, and build knowledge around the public health concepts of family health, disaster planning, and home safety assessment. The guided reflection questions within each module asked the students to reflect on prior experience and construct new meaning.

9.5.2 Goal of the Public Health VRS

The goal of constructing meaning related to public health clinical competence related to the learning outcomes after completing these VRS modules was attained. Students were found to have increased clinical reasoning skills, increased competency levels, and increased knowledge relevant to the population-focused nursing role, and the understanding of population-focused principles in the care of at-risk populations. In addition, students were able to critically analyze health disparities and barriers to adequate healthcare, community assets/resources for improving health quality from an ethical perspective; and be able to evaluate evidence-based public health nursing interventions to address health disparities in a given population. All fifteen students enrolled in the course achieved the established learning goals as evidenced by their individual reflection papers, module quizzes and online discussion forum entries.

9.6 Conclusion

When designing and implementing virtual reality simulations for healthcare education, it is helpful to follow a model that informs not only the design of the simulation, but also how one operationalizes the VRS. To move educators from teaching knowledge and delivering content via traditional lectures to collaborating with students in the application and decision-making process, it takes an intentional framework. The use of virtual reality simulations as a teaching/learning pedagogy can lack meaning and context unless the learning activities are well planned and designed. Through application of the VRS Educational Model, learning activities can be designed, leveled, and supported through timely scaffolding in proper amounts to make the learning meaningful.

We started this chapter discussing the pedagogy of using virtual reality and Second Life as a teaching/learning strategy that can address the increasing complexities within the healthcare milieu. We offered exemplars of several VRS activities from nursing courses that took place in the virtual space of Nightingale Isle. Within these courses, the VRS activities were designed with specific outcomes in mind while incorporating evidence, taking into consideration the knowledge level and technical abilities of the learner. Throughout the implementation of these VRS activities, the students were encouraged to interact with one another, make connections between prior experience and current learning, reflect on the learning, and debrief after the VRS activities. Furthermore, there was a need for intermittent monitoring and evaluation of the technology and learning in order to provide scaffolding to the learners at appropriate intervals.

There are endless possibilities for the use of VRS activities to address the complexities of healthcare education. The virtual environment affords opportunities for unique collaborations and consistent learning experiences amongst students, healthcare professionals, and educators that are not available in the traditional classroom, laboratory, or clinical settings. It is important that faculty balance the time spent developing the VRS and orienting participants, as well as attending to activities related to conducting and evaluating VRS activities. By using the Virtual Reality Simulation Educational Model, virtual learning activities will be developed with the overall goal of increased clinical reasoning, competence, knowledge and the ability to construct new meaning that will transfer to, and improve care of, patients/clients in the clinical practice setting.

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Chapter 10
Improving Health Information Literacy with Games in the Virtual World of Second Life

Elisabeth Jacobsen Marrapodi

Abstract This research project studied how innovative gaming methods using new technologies, such as the virtual world of Second Life, could be utilized to improve health information literacy, and possibly influence future health care decision making. The subject areas of heart attack, stroke and basic medical terminology were selected for interactive health games in Second Life since that platform already has been used extensively for educational purposes, especially in the areas of health promotion. The 3-D virtual world environment provided an immersive arena for developing creative methods of health information literacy delivery and outreach to a global, online community in real time. A key component of the study was the post-game survey asking participants if they had learned new health information and whether that information would be used for future health care decisions. The results are encouraging about the potential use of virtual reality as a platform for health games to improve health literacy.

10.1 Introduction

The U.S. Department of Education estimates 80 % of adults aged 16 or older do not have proficient health literacy [1] which is defined in Health People 2010 as "the degree to which individuals have the capacity to obtain, process, and understand basic health information and services needed to make appropriate health decisions" [2].

Addressing health literacy is important as it impacts all aspects of our lives, from how we communicate with our health care providers to being associated with adopting less healthy behaviors, putting ourselves at risk for higher hospitalization rates, errors with medication and compliance to not being able to recognize the signs and symptoms of serious medical conditions, and knowing when to seek

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treatment, as well as poor management of chronic diseases. However, according to the U.S. Department of Health and Human Services when people receive or have access to health information that is more easily understood and explained, they are much more likely to take charge of their health and wellness. Accordingly, it is essential to make basic health literacy a public health priority.

10.2 Background

While 169 million U.S. adults representing 72 % of the population went online seeking health information in 2010 [3], 90 million people were unable to adequately understand and use this health information for them to be able to take an active role in managing their health. Unfortunately, most health information is presented in such a way that is confusing or isn't usable for the average health consumer.

Furthermore, low health literacy can affect anyone, regardless of their age, race, education or income [4]. Without a clear understanding of basic health information, people are more apt to have worse health outcomes and to increase health care costs [5]. At this time, it is estimated that inadequate health literacy costs the United States between $106–236 billion dollars annually [6].

With approximately 89 million U.S. adults using social media for health in 2010 (up from 38 million in only 3 years), e-tools on the internet have the potential to help people manage their health and health care [7]. This has helped to make the internet a primary driver to empower consumers to make their own health care decisions and to also ask informed questions from their caregivers [8–10].

In addition to the internet, gaming has rapidly emerged as a contender for improving health behavior, encouraging healthy lifestyle habits, initiating behavior modification, and for helping people to manage illness, as well as chronic conditions. By utilizing games to promote health changes, the patient becomes involved in his or her own health care through fun technology for the purpose of preventive or corrective interventions [11].

Online Games can engage players in a self-paced, friendly, private, non-threatening way which at the same time can be an effective medium to educate and inform. This informal play approach for learning is supported by educational research which suggests that this format effectively engages the learning process [12].

The roles of medical librarians have shifted to incorporate new environments, such as virtual reality, and the delivery of health information can now take on a vastly different form than traditional methods [13]. Emerging technology platforms, such the 3-D immersive virtual world of Second Life (SL) are increasingly being used for education, training and outreach in the areas of medicine, nursing, psychiatry, and especially with consumer health to increase awareness about health issues since it provides unique opportunities for educating and disseminating information about health issues [14–16]. Gorini noted in 2008 that

"3-D virtual worlds provide users with a more immersive and socially interactive experience, as well as a feeling of embodiment…" [17].

Indeed, virtual reality has proven to be an effective alternative environment tool with potential to impact health literacy and real life health behaviors, which is very appealing to those seeking options from the more traditional methods of information delivery. This alternative immersive environment can also be of value for continued professional development for librarians as they further collaboration and support for development of future health literacy promotion [18].

10.3 Setting

The Trinitas Regional Medical Center (TRMC) Library is part of a Catholic teaching medical center located in Elizabeth, New Jersey, which is the 4th largest city in the state. The Sisters of Charity of Saint Elizabeth sponsor the hospital in partnership with Elizabethtown Healthcare Foundation. Established in 2000, TRMC offers 541 beds, a variety of teaching Residency programs, and is distinguished by ten Centers of Excellence, which include a comprehensive cancer center, and the Trinitas School of Nursing, the second largest nursing school in the nation.

The Trinitas Library and Information Center serves a large customer base comprised of medical and nursing students, residents, nurses, hospital staff, patients, their families, and the outside community, representing more than 50 countries, and 37 language groups. The Library's consumer health services include public access computer stations, a consumer health book collection, plus free wi-fi. The Library also participates in community outreach through local community health fairs, and offers a program called the Consumer Health Information Partnership Program which provides upon request, consumer level health information mailed to the customer's home or hospital bed free of charge. In early 2010, the Library extended their consumer health outreach mission by entering into Second Life to connect the public to health information.

What is the virtual world of Second Life? Created by Linden Labs in California in 2003, this virtual world is a free, computer based multi-media simulation platform that offers a myriad of experiences for its players, called "residents." Inside this 3-D world residents can experience a feeling of immersion in a variety of virtual reality settings. These settings or environments are created by individuals, businesses, organizations or universities from around the world with the intent to entertain, educate, collaborate, express art, role play, or simply to connect and form relationships [19].

To exist in-world, all SL residents must use avatars which can range from standard game issue to custom designs. Some recreate themselves or choose to be whimsical characters, such as animal shapes, fantasy creatures, role play as pirates, historical figures or anything in between of their choosing. Whatever the representation, Wong's summation of an avatar was that "there is a real human being behind every avatar—the people are very real. It's just the medium that is different" [20].

People are free to choose how they want to experience virtual reality, from casual play to learning. SL is a very social environment and one of the most popular past times are parties where avatars gather to chat, using text or voice, as they listen to music, and even dance by using animations. There is much to do within virtual reality, from exploring historical recreations, attending online classes, teaching, conference or anything else the imagine can conjure.

At this time, SL is one of the most well known and popular virtual reality worlds with over 36 million created accounts and has more than 1 million monthly visitors from around the world communicating, playing, learning and networking in real time. In their 10th anniversary report, Linden Labs had $3.2 billion USD of total transactions for virtual goods, of which $1.2 million are from daily purchases of virtual goods [21]. This thriving economy based on United States currency called Linden dollars can be purchased or earned. Residents also have the option of converting their Linden money into real cash (www.secondlife.com, http://lindenlab.com).

Although SL offers a plethora of activities, from fun to serious, SL has established itself with a commendable track record for educational purposes, such as in the areas of medicine, nursing, psychology and consumer health [22].

There a number of excellent examples for SL health education, some of which no longer exist but are worthy of mention, such as the San Jose State University's Heart Murmur simulation, the former Ann Myers Medical Center used as a nursing and medical teaching center, the hallucination simulation demonstrating schizophrenia created by the University of California, Davis for mental illness education, the University of Illinois School of Medicine's NewWorld Clinic, the Second Life Education New Zealand (SLENZ) midwifery simulation project, The Birth Place, VNEC (Virtual Neurological Education Centre, University of Plymouth, Devon, UK), Virtual Ability Island, Healthinfo Island (created by a team of medical/consumer health librarians), the Mayo Clinic and there is even a 3-dimensional tour of the testes and ovaries (University of Plymouth, UK Sexual Health sim), to mention a few [23, 24].

10.4 Design

The Librarian had already established an in-world presence with the virtual library and academic communities at the Alliance Library System's Info Island. This experience proved an invaluable for networking and connecting with virtual colleagues. Later on, this foundation proved to be a vital component that contributed to the success of our project.

Our study received Institutional Review Board (IRB) approval for one year under Innovative Uses of Information Technology, however we continued to monitor and gather data after the official study expired since there was still a lot of activity with the games, as well as interest in the project.

The study team consisted of the Librarian who collaborated with a team of nursing advisors from the areas of Cardiology, Neurology and Education for the development and creation of all the clinical content for the health games.

Fig. 10.1 Visitors at HealthInfo Island playing the health games

Additionally, we took advantage of technology by recruiting a long distance virtual intern. The primary duties of our library school student from the University of Denver, Colorado was to assist the Librarian with technical design within SL since the nursing advisory team elected not to journey in-world.

The topics of heart attack, stroke and medical terminology were chosen for the games because despite the availability of health information, oftentimes people do not understand it. As a result, people are dying from cardiovascular disease at an alarming rate, with 1 American dying every minute from a coronary event. New data from the American Heart Association (AHA) found that little improvement has been made over the past 13 years in people, especially women, in knowing about this health threat and stressed the need for improved education [25, 26].

Even though death from stroke has declined to 1 in every 19 deaths in the United States, on average someone still dies from stroke approximately every 4 minutes [27]. Therefore, we felt it equally important to include this subject, especially since many people do not always recognize the seriousness of the signs of stroke and may delay treatment while the damage becomes irreversible [28].

The need to educate and prepare consumers is essential to possibly improve outcomes. However, because health information is already readily available in print and online, the Librarian wanted to test a different approach for health information outreach by using emerging, innovative technology.

Everything in virtual reality must be visually engaging so to keep the display interesting to the eye, a brightly decorated virtual exhibit was created to house the health games. Free health themed t-shirts were offered to all visitors, whether or not they played the games, note cards with leads to in-world support groups were available, and videos about heart attack and stroke were also incorporated around the exhibit (Fig. 10.1).

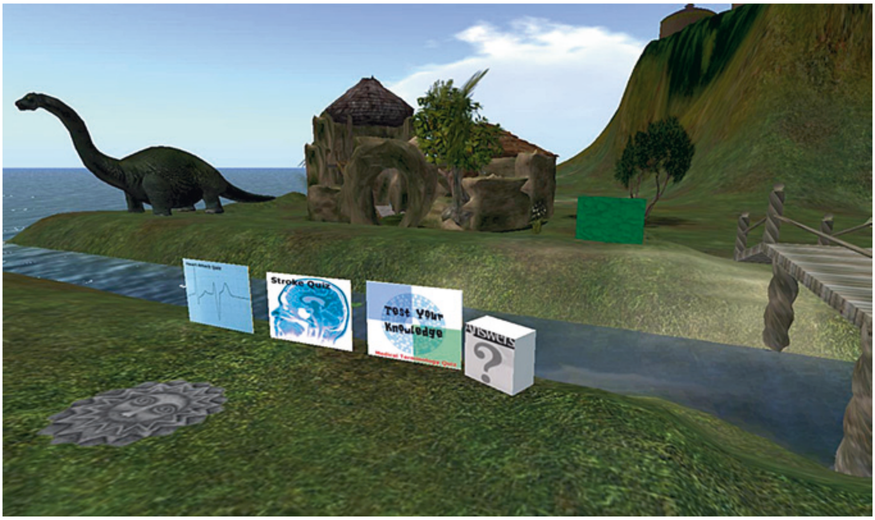

Fig. 10.2 Smaller health games displays were exhibited throughout second life

Fig. 10.3 Permanent exhibit, University of Illinois School of Medicine, SL

Participants were invited to test their health knowledge through a variety of venues, from in-world classified ads, event announcements on the SL webpage, through professional groups, university classes, conferences, and social media tools, to mention a few. Participation also occurred by chance from passers-by at various host site locations throughout SL selected to capture a diverse audience, from universities to such unexpected locales as the Dinosaur Park (Figs. 10.2 and 10.3).

All participants were allowed the freedom to play one or all of the health games. Each game offered untimed sessions to answer multiple choice questions. After every incorrect answer, the correct answer was given with additional information. If the participant answered all the questions correctly they were given a small, nonmonetary prize for their time and effort. At the conclusion of every game, all participants were invited via a pop-up box, to participate in an anonymous, confidential post-game survey hosted outside of SL on the web based program, SurveyMonkey.

The survey consisted of 9 short questions, including several key questions designed to measure the potential of gaming as an effective method to deliver health information with the end goal of improving health literacy.

The key questions were:

- Did you learn anything new about heart attack?
- Did you learn anything new about stroke?
- Did you learn anything new about medical terminology?
- Do you think the new information you learned will be useful with your health care decisions?

10.5 Data

The survey gathered some basic demographic information about the participants to help us formulate a broad picture about who were playing health games in virtual reality even though not all the sections were answered by the respondents. Contrary to initial speculation from some of the team that mostly young adults would be in-world, the survey feedback instead revealed players in SL represented a wide range of age groups, including the elderly.

Although it came as somewhat of a surprise that the elderly were present in a virtual world environment, it was already known that older generations had embraced the internet as a source for health information. In 2002 a study reported 71 % of older people 50–64 years old turned to the internet for health information compared to 53 % of younger people 18–29 years old [29].

It should be noted that for a long time the 41–50 age group held a large lead statistically in our survey results. However, after the Librarian started to actively present to college level students at virtual university and college classes, there was a significant shift in the demographics since professors encouraged their students to participate.

Survey Results: 224 respondents

Age ranges

- Ages 18–30 38.3 % (85)
- Ages 31–40 18.0 % (40)
- Ages 41–50 18.9 % (42)
- Ages 51–60 17.1 % (38)
- Ages 61–70 7.2 % (16)
- Ages 71–80 1.4 % (3)

The survey results also revealed a large gender gap amongst the in-world players with 30.9 % (68) male compared to 69.1 % (152) female.

Players also tended to be well educated. 4.1 % (9) indicated an elementary grade school level education, 12.3 % (27) a high school diploma, 3.6 % (8) a technical school diploma, 15.5 % (34) had some college level education, 23.2 % (51) achieved a college degree, 9.5 % (19) attended some graduate school, whereas 36.8 % (81) held a graduate school degree.

English was the primary language spoken by 74.5 % (161) versus 25.5 % (55) who said it was not. Of those who did not speak English as their primary language, the other languages were: Spanish 14.9 % (10), French 4.5 % (3), Dutch 9.0 % (6), German 6.0 % (4), Italian 4.5 % (3), Portuguese 6.0 % (4) and other 55.2 % (37).

Although the Library had been awarded a Small Projects Grant by the National Library of Medicine, awarded funding was earmarked specifically for promotional and presentation activities, and not in-world project expenses. Thus, having no funding within SL, the project's design expenses were absorbed primarily by the Librarian. Fortunately, we received incredible support from colleagues, friends, and even strangers within SL who generously offered to partner with us. They hosted our health games at several virtual libraries, academic institutions, and professional and private communities within Second Life without charge. Without the aid of our hosts, our project would not have reached its maximum outreach potential.

10.6 Challenges and Lessons

SurveyMonkey collected all the post-game survey data but within the virtual world setting we were limited as to how the data could be collected. As part of a class project, a volunteer student designed a custom game counter for our use. All objects need a programming language called Linden Scripting Language or scripts for short, to move, react or to collect data. The script created for us was supposed to collect how many times each game was played but the script experienced occasional glitches. The counter sometimes stalled and stopped counting without warning. Although the intern and the Librarian visited each of their assigned host sites weekly to collect the data, we occasionally needed to reset the counter.

Therefore, due to the data slippage, the total number of games played is an approximation. Since data was not being gathered during the time period when the script stalled, the number of games played is most likely much higher than reported. With all its innovation, SL is still an evolving, less than perfect virtual world.

In SL everything must be created or purchased. If not purchased, creating objects and building requires a skill set of basic 3-D modeling concepts. These can be self-taught, learned through friends or from in-world classes. Unfortunately, neither the Librarian nor the intern anticipated the scope of these skills and immediately ran into stumbling blocks. Luckily, we were able to quickly master enough basic building skills to create the gaming display.

There were many lessons learned. We quickly discovered plans needed back up plans, and that flexibility in virtual reality was not only necessary, but crucial if we were to succeed. There are expenses in SL, from taking pictures to uploading textures from the computer, to paying for scripts, supplies, even for renting or buying virtual property. Virtual land, referred to in-world as “sims” or “parcels” costs real currency to buy or rent from the Linden server, upwards to hundreds of dollars each month. Once the exhibit was built, a main hurdle was where to house the project since we had no funding to purchase or rent virtual land space. Without permission from a land owner, we had no place to show our exhibit. But, many stepped up to the plate to help.

Our team is indebted to the many SL librarians, educators and residents who offered their help and support because they believed in this project; the university student who created the gaming script free of charge as his class project, the librarians at Healthinfo Island who heard about our obstacles and came to the rescue by providing our first display area for the gaming exhibit, all those who took time to teach us building skills, those who gave us items, plus the generosity of one resident who custom built a podium to display a virtual interactive medical dictionary. Without them, this SL consumer health literacy project most likely would not exist.

Our health literacy games exhibit made its debut on Healthinfo Island in 2010, however, due to restructuring, the exhibit was relocated several months later to the University of Sheffield’s Infolit iSchool site (Fig. 10.4), where it remains to this day as a permanent exhibit. A smaller version is permanently housed at the University of Illinois School of Medicine’s NewWorld education center, and until recently at Bradley University Library and Montclair State University’s Consumer Health Information and Education Center (CHIEF).

10.7 Promotion

We did not have a “build it and they will come” philosophy with this outreach project. Early on, we realized the success of this project would rely on creative marketing since a virtual world does not offer the same type of advertising venues as the real world.

To maximize awareness about the games, the Librarian actively promoted the games through many venues, including creating a Twitter account for her avatar. She joined professional and educational web-based groups and, forums, presented at over 11 professional level virtual conferences and was an invited speaker for SL based university classes, such as The College of New Jersey and other organizations.

Because SL’s social culture revolves around parties and music, the librarian organized many themed events with entertainment and speakers, such as the “Dr. Who for Health Literacy” for World Stroke Day, “Health Literacy Awareness Day,” co-sponsored by the Glasgow Caledonian University, featuring a performance by real life Pipe Major Rik Xaris from Scotland, a “King and Queen of

Fig. 10.4 Permanent exhibit, Infolit iSchool, University of Sheffield, SL

Hearts" dance in celebration of American Heart Month held at Infolit iSchool, to describe only a few (Fig. 10.5).

Other promotional activities included in-world news sources, newspapers and the Librarian's avatar was even interviewed on a live talk show on SL television.

Promotion for the health games also extended into the real world. The Librarian actively promoted outreach through hospital sponsored community health fairs on the local level, and was a speaker at national and international conferences (Fig. 10.6).

10.8 Results

Over the past three years our health games have been played more than 700 times by people from around the world who wanted to test their knowledge about heart attack, stroke, and medical terminology in Second Life. As stated earlier, this

Fig. 10.5 Event promoting health games at Glasgow Caledonian University, SL

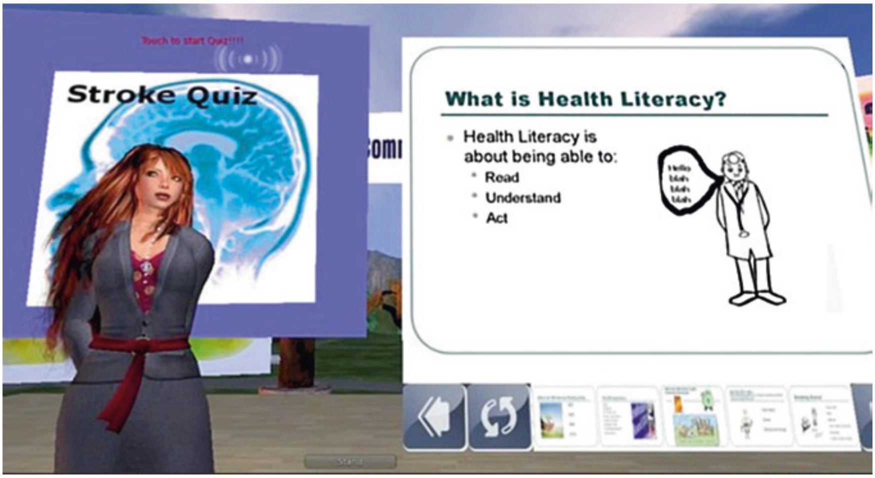

Fig. 10.6 Librarian's avatar presenting at a second life conference

number reflects only the times played as reported by the counter. The true number of games played is most likely much higher. Over 32 % of players submitted feedback through the post-game survey.

Key survey questions:

- Did you learn anything new about heart attack?
  - Yes 56.0 % (14) no 44.0 % (11)
- Did you learn anything new about stroke?
  - Yes 52.0 % (13) no 48.0 % (12)
- Did you learn anything new about medical terminology?
  - Yes 75 % (162) no 25.0 % (54)
- Will the new information you learned be useful for future health care decisions?
  - Yes 72.0 % (18) no 28.0 % (7)

10.9 Conclusions

Immersive virtual reality worlds, such as Second Life show great promise as a venue to foster consumer health literacy. Virtual worlds offer a unique platform for real time communication with a diverse and global population, strong professional networking base and social environment. Virtual reality is also a viable, cost-effective tool for outreach with great potential for impacting real life behavior and decision making for health care. Second Life, as an interactive technology, should be considered an effective tool in promoting health behavior change [30].

This study supports our hypothesis that online and virtual interactive health games can be a fun, engaging, low-cost and effective learning tool to increase health literacy, empower the consumer, create a more informed community which in turn, will ultimately help people manage their health care needs and decisions since behaviors from virtual worlds can indeed translate to the real world [31].

We believe the results of our ongoing study will encourage game based learning in the e-health consumer education arena. Since one of the key missions for health sciences librarians is connecting consumers to medical and health information, we have a window of opportunity to help the public overcome the challenges of health literacy by exploring new strategies to communicate and disseminate health information [32].

10.10 Update

Due to the popularity of the health games in SL, in late 2012 a new section specifically focused on women's heart health was added. In response to feedback, we plan to continue our consumer health outreach and plan to update the games and add new health topics in the near future.

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Chapter 11
Urban Exergames: How Architects and Serious Gaming Researchers Collaborate on the Design of Digital Games that Make You Move

Martin Knöll, Tim Dutz, Sandro Hardy and Stefan Göbel

Abstract This chapter presents a novel research collaboration between architects and computer scientists to investigate and develop mobile, context-sensitive serious games for sports and health (so-called exergames). Specifically, it describes a new approach that aims to design exergames which interact with the player's built, topographic, and social environment in a meaningful way and presents strategies on how to integrate research on health-oriented urban design and planning to the design of such games. To that end, this chapter analyzes the state of the art of mobile context-sensitive exergames and introduces the reader to the basics of "Active Street Design". After recapitulating how the built environment influences physical activity such as walking, cycling, and stair climbing in everyday situations, it is speculated on how to integrate best practices and guidelines from architecture into the game design process in order to create attractive and more effective exergames. The chapter is concluded with a discussion on strategies to validate the (positive) side-effects of urban exergames and an outline of future research directions.

11.1 Motivation

The advance of child obesity, especially in western countries, is a well-documented phenomenon [8]. As obesity is known to promote a variety of medical disorders, such as diabetes and hypertension, this trend is likely to turn into a severe problem for societies as a whole within a few years. People affected suffer from a shortened

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life expectancy and oftentimes report a generally reduced quality of life [24]. Consequently, the fight against childhood and adolescence obesity has become a major challenge for governments, medical institutes, and fitness professionals alike. It is often pointed to the various causes for obesity including an increase of calorie intake and decrease of physical activity on a population level, social environments, individual lifestyle choices and genetic disposition. James et al. [14] highlighted that genetic disposition would make a major difference in individual susceptibility to weight gain among people living in comparable environments. In their view, it is therefore obligatory to oppose the numerous prejudices and immense pressure that is put on obese children and adults' excess weight. The most appropriate response would be to consider environmental circumstances and peoples' particular needs for help. In our view, one possible route to answer this demand is to bring together the dynamic, adaptive, and personalized nature of digital applications and the highly influential—but more static—aspects of the built urban environment in order to unfold meaningful, exciting game experiences that stimulate to navigate and move through, experience, and play within the city.

Elsewhere, Knöll and colleagues have described the "spontaneous" character of such location-based and ICT-supported interventions for health [20]. In addition, it is crucial to emphasize the role of serious gaming for stimulating physical activity. One just needs to watch a group of children or adolescents play catch in a public pool during a hot summer's day or throw snowballs at each other in the freezing winter to realize the power of fun when it comes to making people move, especially those of young age. Using fun as a driving factor in order to motivate a desired behavior with intended side-effects (such as physical activity or learning) is the core idea of serious games [12]. The designers of these games combine "serious" applications, such as educational software, with game elements that are meant to enhance the user experience and to motivate users to invest additional effort into the tasks given, such as the solving of mathematical problems. The better a given serious game is designed, the more the application feels like an actual game and the less the user realizes the side-effects of "playing", for example that she is also working on the improvement of her math skills.

An important subgroup of serious games are the so-called "exergames", the term being a combination of the two words "exercise" and "game" [2]. These games demand the player to be physically active in order to succeed in the game, for example by running, cycling, or dancing (as determined by appropriate sensors). Media researcher Debra Lieberman observed the effects of popular exergames on players [21] and stated that "there is growing evidence that frequent exergame use helps people stay fit and manage their weight". Mobile exergames are a variation of exergames that are not played in front of one's TV screen or computer monitor, but while being outside and on the move. They usually require a smartphone or a portable video game console to be played on. Game designer Ian Bogost already hints to the fact that exergames could interact with the player's built and social environment [3] and Knöll and Moar [18] have pointed out in more detail how different mobile exergames interact with the built environment in various ways. Elsewhere, Knöll [16] states that while urban games have been subject to research in both disciplines respectively—urban design research and computer science—few scholarship has so far dealt with the potential synergies between urban planning and (mobile) health games in particular. The newly established research group "Urban Health Games" at the Technical University of Darmstadt, Germany, investigates health-promoting effects of the built environment in its various physical, social, and cultural dimensions and how these effects can be further researched and augmented by context-sensitive digital games. The group is established at the architecture department and is associated to Multimedia Communications Lab, where its members closely interact with the Serious Gaming group.[1]

In this chapter, we will elaborate on the concept of urban health games and further specify our approach for exergames. Specifically, we will describe how architects and computer scientists, as well as game designers, health and sport experts, nutritional experts, psychologists and others should collaborate in order to design mobile exergames that interact with the player's built environment. By utilizing the knowledge of how the urban environment affects people's activity and movement patterns, we believe that we can build digital games that will inspire and motivate their players to explore and interact with their city. On that basis, we seek to increase the players' general level of physical activity as such is a crucial aspect of a healthier and more satisfying lifestyle. In turn, the experiences gathered by the players should be returned to urban planning experts to assist them in their tasks of designing "active" built environments that also foster peoples' health and wellbeing.

11.2 The Road Behind: Influences on Urban Exergames

Urban exergames are a highly interdisciplinary concept which roots in such diverse fields as architecture and urban planning, healthcare sciences, and serious games research. In this section, we will analyze the two-way relations between these scientific fields and detail their implications on the mutual intersection of all of them, of which the concept of urban exergames originates (see Fig. 11.1).

11.2.1 Mobile Exergames

When we talk about exergames, many readers may inevitably think of Nintendo's *Wii Sports*, a set of sport simulation games such as tennis and golf, played in front of one's TV using a wireless hand-held controller. In Mid-2013, almost 82 million copies of the game had been sold, making it the bestselling Wii console game by far and indeed, the overall bestselling video game up to date across all platforms.[2] This proves the existing public interest in exergames and may indicate that people are willing to invest time and money in these types of games. Of course, the observation itself does not give away as

[1] http://www.stadtspiele.tu-darmstadt.de

[2] http://www.nintendo.co.jp/ir/en/sales/software/wii.html

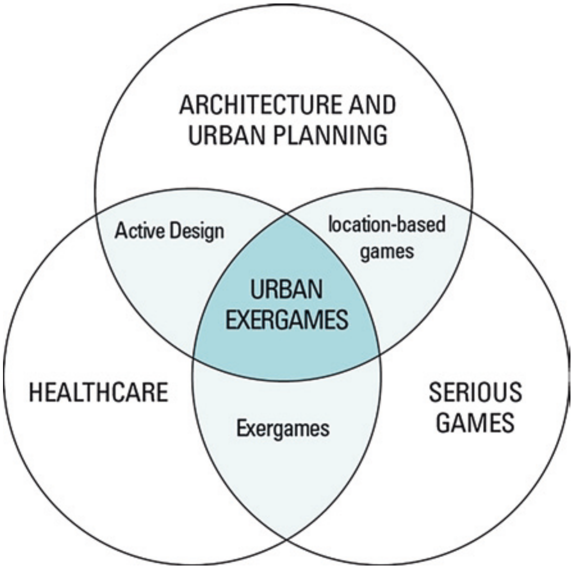

Fig. 11.1 Relevant influences to the field of "Urban Exergames"

to why people buy exergames such as *Wii Sports* in the first place. Is it based on curiosity, the desire to be entertained, or an actual ambition to work out and increase one's fitness level? On a second thought, however, it becomes clear that this is actually not of relevance, as long as these games are designed in a way to keep the user motivated to play on a regular basis, as the intended side-effects (improved health and wellbeing) will be received in either way, regardless of the initial intentions as to why the game was bought (curiosity, fun-seeking, or fitness-striving). At this point, we will thus simply postulate that exergames are already established in the interest of a wider public audience and that there seems to be a demand for these types of games. Researching exergames, however, is a relatively new subject. We have been able to identify only a few number of research groups across the globe that focus specifically on the design and development of exergames. The groups we have found are either based in the field of healthcare and sports sciences [30] or serious gaming research [25].

A variant of exergames are mobile exergames that run on smartphones, usually played outside while the player is moving through an urban or rural environment. These games rely on the device's built-in sensors (e.g., GPS, accelerometer) and interaction capabilities (e.g., display, microphone) to deliver the gaming experience. One such game is *Zombies, Run!* by the British company *Six to Start.*[3] The game seeks to motivate joggers by involving them into an audio story that revolves around a post-apocalyptic world in which the larger part of the population has been transformed into mindless, man-eating monsters (the name giving "zombies"). The player listens to the story bits using her smartphone's headphones while physically jogging, being addressed in person by the actors of the story as "Runner 5". The audio story establishes the idea of a small community of "survivors" that, albeit in constant

[3] https://www.zombiesrungame.com

danger of being attacked by the roaming zombie hordes, has managed to construct a small and relatively safe encampment. However, this group of survivors is always short on vital resources (such as food, batteries, and medicine) and so, volunteers need to leave the compound and search for these resources outside, staying on their feet in order to not fall prey to the wandering monsters. The player fulfills this task of searching for resources simply by physically jogging a certain distance while listening to the background story. Optionally, the player can also activate "zombie chases" and then needs to physically outrun a group of virtual zombies (the chase is indicated by approaching grunts and panicked "radio messages" from other "survivors") or otherwise lose all resources collected so far. Although we can anticipate that the fictional and somewhat brutal scenario may not be for everyone, the huge success of this app, being the best-selling fitness-related application for mobile devices at one point,[4] and its concept on how to motivate players to exercise harder makes this a very important contribution to mobile exergaming as a whole. It seems to be entertaining for many users to outrun a horde of zombies and to bring home a (virtual) backpack full of vital resources, while the training effect is secondary and nevertheless achieved. We consider this a great example of good exergame design. Additionally, the commercial success of this application proves the demand for mobile applications that make outdoor exercise "fun" and paves the way for similar approaches.

11.2.2 Location-Based Games

The concept of digital location-based games is a far more established research field, which can be traced back to at least a decade ago. In May 2000, the so-called "Selective Availability" that differentiated between civil and military users of the GPS system was disabled, resulting in a highly improved accuracy of GPS-based localization for civil users. This brought forth a variety of concepts for games that integrate the player's physical location into the game experience, among them the still popular game of Geocaching [29]. Smartphones with their integrated GPS receivers made playing these games easy, as the user did not have to bring an additional device besides the smartphone that she was carrying with her anyway and thanks to this, location-based games were able to naturally integrate themselves into the players' daily activities. Shortly after their emergence, more sophisticated digital location-based games like Foursquare[5] established the concept of gaining points and achievements for physically moving to and then virtually "checking-in" at specific Points-of-Interest within one's city, such as restaurants and shops, thus motivating players to visit certain locations more frequently and subtly modifying their movement patters within their urban environment.

A very recent addition to the family of location-based games and a game with the potential of becoming a huge success is the game *Ingress*[6] by *Google*. The game is

[4] The Twitter feed of the developer studio, proclaiming the apps' commercial success: https://twitter.com/ZombiesRunGame/status/174164902926229504.

[5] https://foursquare.com/

[6] http://www.ingress.com

currently only available for Android-based devices and even then only by "invite" (one can apply for access to the game at the game's website). However, already today, *Ingress* is vastly popular and one can easily find many magazine reviews, blog entries, and user-made videos online that show the excitement that some players have about the game. *Ingress* is an augmented reality game in which the players have to initially decide for joining one of two competing groups (either the "Resistance" or the "Enlightened") and then conquer virtual portals that are distributed around the world. In a nutshell, the group that holds the larger number of portals in an area dominates this specific area and "is winning". The game makes use of various game mechanics to keep players motivated (such as player levels, virtual items, and the like), but also draws much of its allure from the fact that players are called "agents" and made believe that they belong to some sort of secret society whose members fight a secret battle unnoticed by the public. From our perspective, *Ingress* is an important game for two reasons. First, it is a location-based mixed reality game that motivates players to physically explore (and thus move through) their urban environment while hunting for portals and virtual items. Although hardly mentioned by the project designers, physical activity is a key feature of the gameplay and may therefore have positive effects on the players' wellbeing. Second, the virtual portals are usually located at real-life statues, buildings, or works of art. By interacting with a virtual portal, the player implicitly also interacts with her built environment. Even more importantly, players can propose the establishment of new portals by taking an image of the site where the portal should be located, marking it on a map and then sending the information together with a short descriptive text to the *Ingress* development team. The game developers will then decide "within a few weeks" whether a new virtual portal will be established at this specific location. This feature gives players the opportunity to select specific elements from their urban environment and (eventually) have them integrated into the game. Through this, *Ingress* may manage to establish an emotional attachment between players and urban places. Based on these observations, we feel almost inclined to call *Ingress* a mobile exergame that interacts with its urban environment in various ways. We observe with pleasure the immense popularity that the game already seems to enjoy.

11.2.3 Active Design

In this section, we will introduce research and basic concepts of how the built environment stimulates physical activity in everyday life. Frumkin and colleagues have seen growing evidence for the fact that the physical features of "urban sprawl" discourage physical activity [10]. Frank and colleagues have observed how the three factors of transport infrastructures, land use pattern, and urban design characteristics influence peoples' choices to walk or to cycle on the level and scale of neighborhood communities. Their analyses highlight the importance of densely-populated living areas, in which well-connected street networks prevail as opposed to "cul-de-sacs". They also find multimodal transport networks

Fig. 11.2 Influences on urban exergaming based on Frank et al. [28, 9]

with many stops key to make people walk more in their everyday lives, e.g. commuting to work, school, or university. They emphasize the density of manifold attractive starting points and destinations for pedestrian and bicycle travel, which would result from a diverse mix of usages including housing, retail, and recreational usages, and they point to elements of street design such as sidewalks, green spaces, and lighting [9]. From an urban design perspective, their work relates to a discussion among town planners on car-friendly and "unwalkable" cities that has originated in the 1960s [11] with recent facts on potential negative effects for people's wellbeing. Their work also provides a comprehensive overview into how the built environment in combination with public health policies and activities promotes daily movement patterns. They focus their analysis on walking and cycling as a mode of physical activities that require little or no means to engage in, short time slots, and are therefore being considered as highly accessible [9]. For us, their work raises the question if and under which circumstances we may develop exergames with similar "accessible" qualities and in which way their interaction with the urban environment differs from daily movement patterns (see Fig. 11.2).

In order to better understand how the physical environment may influence exergaming, it is crucial to emphasize in more detail how urban design influences daily movement patterns. More recently, The New York City planning departments have provided a set of “Active Design” guidelines for architects and urban planners based on current research and best practices to stimulate physical activity. The Active Design Guidelines focus on what is in their view a highly influential factor for densely-populated cities as Manhattan, and comparable compact settings in Europe and Asia: The design of our daily environments such as green spaces, squares or cycle lanes [28]. The authors also provide guidelines on an interior level, describing effects of positioning, accessibility, and visibility of staircases within a facility, to actual design features such as stair dimensions, provision of light, colors, and using valuable finishing and materials. And although providing a compact overview on how the built environment influences everyday movement, we find that Active Design concepts need to be extended with a broader scope on how architecture influences movement, which has been articulated by many architects and most recently by Janson and Tigges [15]. Sociologists Robertson-Wilson and Giles-Corti have pointed to a general issue of such cross-sectional empirical studies, which also becomes effective in Active Design research. In their view, statistics merely showing relations between walkability and obesity may hardly resolve the Chicken and Egg-problem. For them, it appears possible that certain design features shape physical activity in its occupants. However, overweight and inactive persons could also prefer to move to areas which are car-friendly per se and that therefore suit their lifestyle of choice better. They insist on the necessity of clear evidence for any guidelines for neighborhood design, since those would provide a blueprint that will influence generations of local residents and claim for further research and improved research design in order to gain deeper scientific insights [26]. We can confirm that we would like to see more research that seeks to underline proposed relationships with more real time data such as GPS supported movement patterns and the assessment of vital parameters.

11.2.4 Other Influential Factors

The main intent of urban exergames is to motivate players to be physically active in, and to interact with their urban environment. Already this condensed summary implies that developers of urban exergames are confronted with questions such as “How to motivate players?” or “What makes a good training?” and therefore will have to collaborate with other research fields. Psychologists for example, can contribute to the development of urban exergames by helping with the conceptualization of mechanisms that adapt the game experience to the different types of players, as people are known to respond to different types of incentives, some preferring competitive and others preferring collaborative types of gameplay [1]. Psychologists are also profound in determining the emotional effects a specific environment has on a player, both “manually” through interviews and questionnaires and automatically by using sensors. Knowledge of these effects is important, as they will influence the player’s mood and thus her inclination to keep playing (and to stay physically active). While psychologists primarily focus on determining and improving the emotional aspects of games, sport scientists are needed for their knowledge in exercise theory and their expertise in the prediction of physiological effects. Depending on the type of game (and its intended audience), the contribution of sport scientists can range from identifying game mechanic aspects that have the potential of harmful physical side effects and up to helping the game developers to create games that optimize training intensity (e.g., by developing concepts for games in which the game experience is adjusted in dependence of the user's heart rate [7].

We conclude this section with the observation that while the main influences on urban exergames come from the fields of architecture, healthcare, and serious gaming, there are also other scientific fields that should contribute their expertise to the conceptualization of urban exergames and thus help in making them reality.

11.3 The Road Ahead: Creating Urban Exergames

In the previous section, we have introduced examples for exergames and mobile location-based games, among them the two highly popular games *Zombies, Run!* and *Ingress*. Indeed, both games can be seen as being mobile exergames, as the player is required to be physically active in order to succeed in the game. This aspect of the game mechanic is more pronounced in the game *Zombies, Run!,* in which the player needs to run a certain distance to acquire virtual items, and somewhat less obvious for *Ingress*, but the necessity of moving to specific physical locations in order to conquer the virtual portals associated to these real world places is nevertheless part of the game.[7] Besides the fact that both games are fun to play and enjoy large player bases, we believe that they could be improved in both ways in which serious games (such as exergames) are supposed to affect the player. That is entertainment (which regards the players' inclination to play and her long-term motivation to keep playing) as well as self-improvement (which, in the case of exergames, regards the amount and the nature of physical activity involved).

Starting with *Zombies, Run!,* the game apparently is quite successful in motivating players to run just the way it is. However, since it does not integrate the player's environmental context into the game experience, we feel that it disregards a huge potential for increasing the player's immersion into the game and thus, a potential for increasing the game's entertainment factor. The game is the same regardless of the location where it is being played at, and while this allows the game to be enjoyed almost anytime and anywhere, it also makes the game feel somewhat generic and interchangeable. For instance, a comparably simple differentiation between the player running on streets, in parks, and in the woodland,

[7] We will ignore the fact that players can intentionally bypass these sportive aspects of the games by using a car or a bus and rather trust in their voluntary compliance with the unspoken game rules.

maybe by distributing the availability of certain virtual items between these alternatives, would require players to plan and possibly dynamically adapt their running routes accordingly and so increase the player's grade of involvement into the game. Technically more challenging to implement, but also more rewarding to the player, would be the consideration of the actual physical location of the player, for example by making in-game references to nearby points-of-interest, by requiring the player to reach certain places in a given time, or by asking her to change her route in order to avoid specific "monster-infested" areas. We believe that these kinds of interactions between a game and the player's environment would have a twofold effect. First, they increase the player's immersion into the game, as they establish a bond between the virtual game and the physical world. This makes the game feel more "real" and allows it to integrate itself more naturally into the player's everyday life. Second, the player becomes more aware of her environment, for instance by having to take new running routes through the city and by having to actively look for parks and recreation areas during those exercise runs to provide for a good diversity of virtual in-game items. Creating this type of awareness for the built environment and its potentials for individual activities and their effect on one's wellbeing is one of the main intentions of urban exergaming.

The game *Ingress* is a location-based game by design. Consequently, there is a strong link between the game mechanics and the specific location where the game is being played at. We believe that the game indeed draws much of its fascination from the fact that, different to classic video games, it is being played in the public, albeit unnoticed by most. *Ingress* motivates its players to conquer virtual portals in their vicinity, and players may get emotionally attached to "their" portals which are associated to buildings or statues near their homes or working places. The fact that players can even create new portals (which are then publically available for all other players to discover and eventually conquer) further intensifies this effect of establishing an emotional bond between a person and a real-world location through the existence of a virtual game element. However, it appears to us that the game designers chose to not exploit the games' potential for also being a full-fledged exergame. While playing the game, no stimulation occurs to move quickly by foot or for regularly having to reach certain, distant locations. The game's primary intention is to entertain its players and the game designers have discovered that embedding a game's virtual world into a player's physical, real world (urban) environment provides for a high entertainment factor. In this case, the fact that the game concept also implies the necessity of a certain amount of physical activity seems to be a probably welcomed, but secondary and ultimately negligible effect.

11.3.1 What Makes an Urban Exergame

We envision the new research area of urban exergames to merge the game designs of mobile exergames like *Zombies, Run!* and of location-based games such as *Ingress* in order to create games that motivate their players to be physically active while they explore and discover their urban environment. The Active Design guidelines, as introduced in the previous section, should be considered during the game design process in order to identify locations that motivate physical activity and thus intensify both the inclination to play and the training effect itself. Furthermore, urban exergames should provide for a way to gather feedback from their users and to pass this knowledge on and into a participatory design processes. Thus, we seek to develop urban exergames as a springboard for communication on the complex relations between health and the built environments, which in the set up of urban planning and co-design processes will help to shape urban environments that motivate and inspire city dwellers to lead healthy and active lives. Based on these considerations, we have identified the following set of criteria that a game must meet in order to be an "urban exergame":

- Urban exergames are digital games that require **physical activity** from their players. As the term already implies, this makes them exergames, serious games that seek to motivate their players to be physically active with the intention of improving their health and wellbeing. Augmented reality approaches seem to provide for more extensive game concepts that also involve the player's upper body into the exercises and thus go beyond the typical "run (or cycle) from A to B" tasks as encountered in many other mobile exergames.
- Urban exergames are made to be played in an **urban environment**. As most of the contributions we have reviewed suggested that the built environment plays a crucial role in the reduction of an average's person physical activity, urban exergames are supposed to help their players in (re-)gaining the motivation for such by re-appropriating public space.
- Usually, urban exergames run as digital applications on smartphones. This **mobility** is a requirement for the creation of universal games that are not bound to a specific area, city, or country and also allows the creation of games that can be integrated smoothly into the user's daily activities, as the smartphone is always at hand.
- Furthermore, urban exergames rely on the smartphone's built-in sensors to perceive the current state of the user and her environment (such as "where is the user at?" or "what is she doing?"). This is a requirement for creating **context-sensitive** games that dynamically adapt the game experience to the user's current situation and for example allow the integration of the user's current physical location into the game experience (such as in location-based games).
- The designers of urban exergames should be aware of the **Active Design guidelines** when it comes to the selection of real-world physical locations to be integrated into the game. Knowledge of relevant guidelines helps with the identification of places that motivate people for physical activity, thus intensifying the motivation for playing and the training effects of the game. Input from urban research can be further specified according to the target group and purpose of given urban exergame projects. Burton and Mitchell, for example, have investigated how people with restrained motoric and cognitive skills navigate within public spaces [6]. What they call "inclusive urban design" may inform

exergames that are being used in training and rehabilitation projects that also thematize aspects of social inclusion and participation.
- Urban exergames should be designed to create **awareness for the built environment** and possibly inspire players to explore and discover new routes through, and new locations within their cities. Once the player base within a given city has reached a certain size, the data acquired from these player activities should be made accessible to urban planners, as it will help them to identify areas that need to be reshaped in order to create more inspiring environments.
- Finally, and most importantly, urban exergames should be **fun to play**. The designers of urban exergames should engage in and access research on popular mobile games such as *Zombies, Run!* and *Ingress* to learn how to create entertaining game experiences, as urban exergames will have no effect on their targeted users if no one wants to play them in the first place.

Summarizing these criteria, we can state that urban exergames are context-sensitive digital games that inspire their players to be physically active in an urban environment and that create awareness for the locations that they are being played at. Of course, even meeting all of these criteria does not necessarily provide for a "good" urban exergame which is motivating and fun to play, that induces a significant and lasting training effect, and that inspires players to explore and discover their cities anew.

11.4 Towards Urban Exergaming

As mentioned before, the Technische Universität Darmstadt has established a research group named Urban Health Games. The group aims to better understand and influence the various potentials for digital games in health promotion and health-oriented urban planning. To that end, it develops and evaluates research projects that vary from exploration games to support navigation through recreational and touristic areas to location-based games that aim to support people affected with type-1-diabetics in documenting their data.[8] In the remainder of this section, we would like to introduce some of the projects that we have been working on since and the first steps that we have been taking towards urban exergaming. A key task on that road, which we have outlined in detail in this article, is to develop strategies to evaluate the correlations between physical activity in the city, the playing of digital games, and their potential (positive) side effects for their users' health. Elsewhere, we have pointed to the limited research available that validates the physiological effects of playing context-sensitive games for health regularly. Even less research focuses on the complex relationship between mobile games, a players' health and wellbeing, and the (urban) environment in which many of these games are being played. We have specified aspects of health-oriented urban design that has been

[8] http://www.stadtspiele.tu-darmstadt.de

shown to influence people's everyday activity patterns including running and cycling. In our view, "Active Design" context can also have an impact on how we play mobile games for health and demonstrates how this knowledge can be used to improve such games [20]. We are currently reviewing current strategies to evaluate effects and usability of digital applications "in the wild"—that is testing games in everyday environments as opposed to lab environments [27]. Our aim is to propose a model, which allows us to better evaluate the various effects on the player by also integrating and further structuring the information of the urban context in which exergames are being used. This model is currently being tested in our own research and design projects and will be further elaborated.

We like to conclude this article by illustrating our approach with some concepts that have been developed by students in current teaching activities both in the architecture and the computer science department at Technische Universität Darmstadt. In a seminar, we asked architecture students to develop conceptual prototypes for an exergame that would critically reflect the Active Design guidelines [17]. The results varied extensively in the way students made use of "space" in their game concepts. In one project, students would adopt the well-known Scotland Yard board game to provide a mobile hide-and-seek type of game for people with a wide range of motoric and sensoric skills. Based on Inclusive Urban Design guidelines, mentioned above, students carefully chose game locations for a location-based game with the aim to make the game experience as accessible as possible. Wide, obstacle-free and wheel-chair accessible paths were chosen and the skills to win the game aimed to balance rushing with navigating the city and site-specific knowledge. A second group worked on a different scale of the built environment by focusing on existing movement patterns that constitute a university student's mobility. Since, in their view, students are exhibiting a sedentary behavior on campus, their target was to identify movement opportunities and increase them. Their concept of a "Word Jumping" game seeks to change the way university students navigate the main building of the architecture faculty by attracting them away from elevators to the main staircase, thus increasing their movement pattern by additional stair climbing. The game is conceived to be a short distraction on the way to the cafeteria, the coffee bar, or just to a different classroom, therefore it can be played at all times, the peak being planned during the lunch break, when most students are likely to be passing in and out of the building. Having learned that the visibility of stairs, its design and finishing with attractive lightening, decorations, etc. stimulates stair climbing, the project seeks to augment the central ramp that overlooks the building's foyer with a word spelling game. The goal of the game is to create a word with the most points possible (either by being very long or by including more valuable letters). In order to achieve this goal, students have to change their sedentary pattern, access the stairs and jump. The students implemented a conceptual prototype as an installation, which featured cardboard pads, a beamer projection and an Facebook page to inform players on scores and results. Their work pointed to many ways to further develop urban exergaming concepts in different set ups and by working together with IT experts.

Fig. 11.3 The game selection screen and the Mee avatar of the GoGreen application

In a new interdisciplinary course format, we are currently developing such a new form of collaborations from a very early stage on in students' curricula. Students from three different departments (architecture, psychology, and electrical engineering/computer science) form a project team in order to contribute each owns perspective and to profit from each other's skills and expertise. Being supported by lecturers of the university's serious games lab, the sensor lab, and the architecture department, the students engage in the full process of developing a new prototype for an urban exergame and they learn important competencies typical for interdisciplinary collaborations.[9] The first course took place during the summer term of 2013 and two teams, consisting of about eight students each, designed and developed urban health game prototypes. One of the results is called *GoGreen* and features a set of small, location-based games to be played at locations in Darmstadt, Germany. The games are connected to one another through a central game mechanic, the so-called *Mee*. The *Mee* avatar changes its appearances over time, depending on the types of activities the player primarily selects from the list of available activities. If, for example, the majority of these activities focus on running, only the *Mee's* legs grow bigger, resulting in imbalanced proportions of the avatar. Obviously, the driving idea here is to motivate players to ensure for a balanced mix of activities that involve the entire body. Figure 11.3 shows a screenshot of the game selection map (on the left) and of the *Mee* avatar (on the right).

The *GoGreen* development team invested a lot of effort into the identification of locations where the small exergames included in the application could and should be played at. To this end, they first identified all suited locations within walking distance from the central university campus to ensure that other students could play their game during lunch breaks. As a second step, they analyzed and rated those selected locations using both the Active Design guidelines and additional guidelines issued by the German *Federal Ministry of Transport, Building*

[9] http://www.urbanhealthgames.de

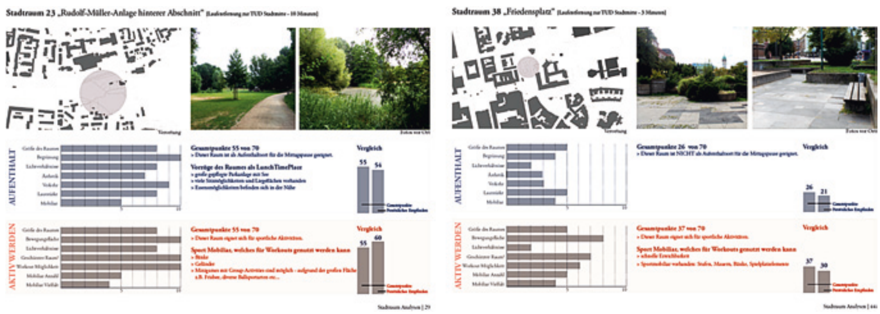

Fig. 11.4 Two site analysis reports, based on the active design guidelines

and Urban Development [5]. Figure 11.4 shows two exemplary analysis reports the group produced. Considering that the students identified and rated well over fifty different locations potentially suited for playing location-based games at, it is somewhat surprising that the games included in the *GoGreen* application itself are playable at only a single location, the so-called *Herrngarten* park in Darmstadt, Germany which can be explained by the limited amount of time available to the students during the term—and by the fact that the computer science students of the group had started implementing the game before the architecture students had finished their survey. This is a vivid example for the communication difficulties that can arise in interdisciplinary teams, and the need for fostering the mutual attunement in such.

11.5 Discussion and Outlook

In this chapter, we have introduced our vision for the emerging research topic of urban exergaming and investigated how urban exergaming differentiates from related areas of mobile gaming such as mobile exergaming and location-based gaming. As urban exergaming is a relatively new addition to the field, the identification of open questions that require further research is not a difficult task.

Certainly, one of the main challenges that we ought to address is to streamline and accelerate the process of how to select the real-world locations where urban exergames should be played at, as these places should meet the Active Design guidelines and must thus be selected thoughtfully. This translates to the question of how to create urban exergames that are not limited to a certain city district or city, but that can also be played in other cities. Games that require a large amount of work and dedication in order to be adapted to other places are unlikely to ever reach a larger audience and as such, they will not make a significant contribution to the fight against obesity in western countries. Consequently, we require an approach that enables game designers to develop urban exergames that adapt themselves automatically, or at least semi-automatically, to the player's individual environment. Various approaches such as a community-based selection process as used for *Ingress* are possible and need to be investigated.

Our medium-term plans for urban exergames include the supervision of multiple interdisciplinary student theses that investigate the design, implementation, and evaluation of different types of urban exergames. Through this, we hope to be able to identify a process that, when followed, helps game designers to create "good" urban exergames, games that are fun to play, that have a significant training effect, and that create an awareness for the built environments they are being played in. On the long-term, we hope that urban exergames will be able to establish themselves as a new type of mobile exergaming that helps to improve people's lives, as the games interact with their daily activities and inspire them to be physically active in their urban environments.

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Chapter 12
Leveraging Play to Promote Health Behavior Change: A Player Acceptance Study of a Health Game

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Abstract Games have become a prominent medium for empowering individuals to manage their health. However, the use of games for health behavior change remains largely understudied; little is known about the mechanisms through which games can effectively engage players or how such mechanisms can affect behavior change. This chapter presents *SpaPlay*—a game designed to motivate players to adopt healthy eating and exercising behaviors. To evaluate the effect of the mechanisms embed in *SpaPlay*, we conducted a mixed-methods study to assess acceptance and adoption of the game. Using game telemetry data and corroborating it with repeated and weekly participant interviews, we document the extent to which rewards to incentivize healthy eating and exercise in the game remained effective. Based on our findings from our study of *SpaPlay,* we also tackle several challenges that remain inherent to designing pervasive health games that can impact long-term motivation and persistence for sufficiently bringing about health behavior change.

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12.1 Games and Health: Opportunities and Challenges

Obesity is a persistent health epidemic, with less (or no) sustainable solutions in sight. Obesity imposes significant financial and health strain on individuals; it is one of the leading causes for several long-term health risks such as coronary heart disease, high blood pressure, or type 2 diabetes [1, 2]. Obesity-related annual healthcare costs have been estimated to be as high as $147 billion and at an individual level. This means, obese individuals tend to spend $1,429 more on healthcare annually than their non-obese peers [3, 4]. Largely, these rising trends are caused by persistent and life-long patterns of inactivity and sedentary lifestyle. For instance, the CDC reports that over 50 % of adult population do not meet even the rudimentary federal recommendations for aerobic activity or muscle strengthening [2]. In elderly individuals, the rates are even higher: over 70 % of older adults between ages 40 and 70 do not meet the requirements for physical activity. Hence, for any obesity-related intervention to remain successful, it ought to be able to sustain a longitudinal commitment towards healthier living. There is, thus, an increasing need to develop affordable and motivating technological interventions that can promote long-term engagement and also be integrable to individuals' life style. As such, recently, there has been a growing emphasis to design and implement solutions to help individuals to manage weight-gain and obesity, and to develop pervasive technologies that can facilitate and sustain long-term engagement in healthy eating and exercise.

12.1.1 Gamification and Long-Term Health Outcomes

While effectiveness of traditional behavioral interventions that can bring about sustainable health behavior change has yet to be determined, there is a great potential for digital games to become a compelling medium to motivate individuals to adopt healthier lifestyle. Considering the reach and popularity of health-based ubiquitous technologies—a recent Pew survey reports that the number of people using smartphones to manage or track personal health went up from 9 % in 2010 to 29 % in 2011 [5]—games can be compelling motivators to incentivize health behavior change. Based on the 2011 report by the Entertainment Software Association (ESA), 72 % of American households play computer or video games, with the rates of 18 % for individuals under 18 years old, 53 % for 18–48 years old, and 29 % for 50+ years old. Internet use and game playing have also been found to be associated, and it has been estimated that 64 % if adult users of the Internet also play video games [6]. This pervasiveness of online social games and social networking is manifested not only in the percentages of users playing games, but also in higher game retention and adherence among on-line players—i.e. a decisive majority of online gamers in the US (89 %) play Massive-Multiplayer-Online Games at least a few times a week [6].

Gamification approaches have already become popular among software vendors and are now being used to improve participant engagement in software products.

Gamification entails integration of game features (e.g., quests, points) into non-game software products in order to make them enjoyable and attractive [7–9]. According to Deterding and colleagues, "…video games are designed with the primary purpose of entertainment, and since they can demonstrably motivate players to engage with them with unparalleled intensity and duration, game elements should be able to make other, non-game products and services more enjoyable and engaging as well (2011)." In short, these researchers argue that games can be compelling motivators that can incentivize behavior change and thus, vouch for designing and studying innovative approaches to iteratively design *playful* experiences to enhance technologies developed to promote activities, such as eating, exercising, teaching and learning [7].

However, in the context of health, there has been limited research examining the potency of *gamification* techniques in effectively fostering healthier eating and exercise habits in individuals. The few research that has been conducted in this domain, has to a large extent, focused on new ways of framing theory of health behavior change in order to evaluate efficacy of health-based technologies. Studies argue that initiating and sustaining health behavior change through games and technologies entails designing technologies based on behavioral theories, such as addressing various stages of change as proposed by the Trans-Theoretical Model (TTM) of behavioral change [10] or the Goal-setting theories as well as addressing social and psychological influences on individuals' lives [11]. Additionally, they further argue that ubiquitous technologies impact behavior through "encroaching upon" individuals' personal as well as their social worlds [11]. Some other works include feature reviews that list design features like content catering to different personality types and multiple challenge levels in the game that can engage players in health-related activities [12]. Yet, none of these have attempted to empirically examine or investigate the impact of such gamification techniques on individuals' longitudinal health behavior change.

12.1.2 Research Questions and Objectives

In this chapter, we present key findings from a research study investigating players' participation, motivation, and adherence to a health-based social media and game environment—*SpaPlay*. *SpaPlay* was designed to promote healthy eating and exercise habits through integration of game-related and real-life activities. We posit that characterizing player motivation and engagement, is an important first step towards developing intervention mechanisms through games that can have a persistent impact on players' health-related behaviors. We adopted a mixed-methods approach, making use of game telemetry data to formulate follow-up interview questions and investigate specific design metrics of the game. In other words, we sought to understand how and to what extent do the game mechanics in *SpaPlay* impact the way participants make choices about food or physical activity in their daily routine? And, finally what makes the participants care about the game and to what extent might SpaPlay have the potential to permeate players overall living style?

12.2 Previous Research in Games and Health-Behavior Change

There are several products (mostly, commercial) that use game elements and real-time tracking for behavior change. These products are designed to increase (a) exercise through exergaming or through tracking of behavior (b) awareness about nutrition and (c) exercise through social networks or gaming. Below we review each of these techniques.

12.2.1 Exercise Through Exergaming

The major principle of Exergaming is to include motion-sensing devices to track movement (e.g., patterns and intensity of activity) and, through positive feedback, motivate players to exert themselves physically. As an example, a user may see a simulated virtual representation of themselves (an Avatar) or a part of themselves (tracked limbs) that reflects real-time movements (e.g., dancing, jumping, stretching etc.). Some popular examples include Nintendo's Wii Fit and Wii Sport for golfing, skiing, running, Zumba for dancing, My Weight Loss Coach and Pokémon HeartGold for walking. Again, studies about exergames show that, through avatar representation and visual display of ongoing real-time activity, players are motivated to engage in physical activity for a longer play session [13, 14] (O'Donovan and Hussey 2012). Further, Song et al. [13] found that the use of avatars is especially beneficial for players with lower body image. One of the core limitations with these types of studies is that they make an inherently limited assumption about health behavior change, thereby only focusing on the immediacy of the activity, how much calories they tend to burn and which game design metrics help promote player engagement within the scope of a play session. While these studies are useful to refine the technological sophistication in videogames and how sensitive they can get to players' needs, they remain challenged in being able to measure the impact of the game on longitudinal health outcomes. In short, while effectiveness of exergames in a single session is encouraging, less is known about adoption of these games and their long-term impacts.

12.2.2 Games to Increase Awareness About Nutrition

When it comes to persistent behaviors related to nutrition, several studies have investigated the efficacy of games in bringing behavior change through empowering participants with information via stories in the game [15–17]. In an in-depth case study, [18] has argued that certain eating habits like selective preference in food that persist for years, are hard to change and posits that simplistic behaviorist techniques, like reinforcement when used in isolation remain ineffective in bringing about behavior change. Rather, a game-based approach is more likely to be effective, particularly in cases where the reason for chronic refusal of certain foods is related to the child trying to establish control and independence. Similarly, a wide-scale study with 241 subjects Amaro et al. (2006) found that an experimental group of 153 children who played a game designed for encouraging healthy eating, showed a significant increase in their knowledge about nutrition ($p < 0.05$) and in their weekly intake of vegetables ($p < 0.01$) compared to the control group with 88 children. Similarly, Thompson et al. (2010) developed and investigated the efficacy of DIAB, an adventure game that sought to increase awareness about different food choices and physical activity by presenting moral dilemmas to the players through the game narrative, whereby the players learn about right and wrong choices for the body (Thompson et al. 2010). Again, this study does not report on measures of efficacy, as much as it advocates for certain theories for behavior change that fit better with health games. In short, such studies, in some fashion, narrativize content or health information and argue that through empowering users with knowledge about right and wrong health choices will allow them to eventually adopt these practices in real-life [15]. Through documenting findings from the player acceptance study of *SpaPlay*, we seek to leverage several of these principles, while also evaluating the efficacy of how well these practices get imbibed in players' lives outside of the game.

12.2.3 Gamification and Persuasive Games

Health behavior change is a complex mechanism that entails more nuanced understanding of individuals' motivation and perceptions about health (Bogost 2007). Thus, evaluating the efficacy of design in health games may become exceedingly limiting if behavior change is tackled within a narrower notion of the intervention [19]. Few research projects within games and health conceptualize health-behavior change as an ongoing and a life-long process for personal health improvement and list out some key aspects in health devices that can improve player adherence. Features, like goal-setting, tracking and monitoring of goals, varying forms of feedback for performance (participatory and individualized) and determining the right balance between goal time frames with individuals' existing routine are critical for designing effective and compelling games-based health systems [11, 20, 21].

12.2.4 Games and Health-Related Social Behavior

Finally, a crucial aspect in gaming that has yet to be explored in the context of health games is social behavior and its influence on health behavior change. Several recent studies point that choices related to food, exercise and even chronic cases of obesity spread through friendship-based or other social networks of individuals [22–24]. These studies argue that *social capital* or an affiliation with a specific social circle, frequency of socialization and level of participation in clubs or associations impact individuals' choices of and trust on sources of information related to health [25]. Social support is also a key determinant of how likely an individual is to seek treatment for an ailment [26] and how well individuals adhere to exercise and nutritional eating habits 27. However, most of these works have been predictors of human behavior related to health in non-game contexts and to our knowledge, not much has been done to exploit social affiliation within games to promote healthy lifestyle choices. In this chapter we also focus on *social dimensions of play* as a critical component that can further improve adherence and "buy-in" for players to engage in the game for longer periods in their lives.

12.3 Study Design

In this section we briefly review the major components of the game, *SpaPlay* and the design of the study.

12.3.1 SpaPlay: The Game and Core Design Principles

Three years ago we formed a collaboration with the game company IgnitePlay. This collaboration was formed to develop and evaluate a social game environment called *SpaPlay* [28]. *SpaPlay* is an online social media environment, where players build and run a virtual "health spa resort." The growth and success of the virtual spa is tied to health-based activities that players undertake in real life. Examples of activities include choosing a healthy snack, including vegetables in a diet, climbing stairs and walking. Real-life activities are subdivided into quests, which are longer chain of activities (e.g., get down one stop before your destination and walk to work, for 4 days in a week) and sparks, which are short and immediate activities (e.g., step away from your desk and stretch for 5 min). Further, the game also has an on-line community of fellow players that can collaborate on mutual activities or compete against each other. All player activities are tracked.

SpaPlay was built under the theoretical principles of Self-Determination Theory (SDT). SDT postulates that human motivation is largely guided by three basic psychological needs: autonomy, competence, and relatedness (29–31). To reflect these principles, *SpaPlay* fosters healthy eating and physical activity through empowering players to manage their day-to-day quests (autonomy), rewards regularity and self-initiated challenges in game quests (competence), and incorporates activities that necessitate intrinsic motivation in day-to-day tasks (relatedness). Further, the game also incorporates some of the motivators deemed critical in Social Cognitive Theories (SCT) for health-behavior change, through

Fig. 12.1 Screenshots of the spa island in the game

appraisal feedback, affirmation, and just-in-time instrumental support [32]. Below we briefly discuss some of the game features.

12.3.2 The Virtual Island

Spa Play is a virtual spa game (see Fig. 12.1), in which players maintain a virtual island or a health spa. In order to maintain the rating of the spa, players do certain routine island-related activities, such as cleaning the running tracks, harvesting fruits from the trees, in addition to accruing points to unlock more game content by doing real-life physical activities and making healthy eating choices. The game play consists of maintaining this virtual island by doing *sparks* or *quests*, which reward the player with points that affects player leveling, provides currency to unlock new game content and improves the resort's overall star-rating. In addition, players accrue points to unlock game content by doing real-life activities related to exercise and healthy eating required by sparks and quests in the game. Table 12.1 presents a description of activities and their intended purpose.

The following presents a short description of each of the gaming activities that can be done by a player in the virtual island, each one of these activities is linked to a game design principle that is used to increase player retention and enhance behavior change.

12.3.3 Sparks

Sparks (see Fig. 12.2) can be thought of as real-time actions in the game that entail doing activities in short bursts, some of which are related to exercise, eating and drinking, and others that are related to tasks in the game world, such as solving a word puzzle. The design intent was to encourage players to develop fondness towards some of the gaming activities, in short bursts, while adding *playfulness* to ordinary or day-to-day physical activities, such as walking till the next bus stop, taking an extra flight of stairs etc.

Table 12.1 Implemented motivational components of Spa play

Motivation tactic	Player actions	Impact on the game
Positive reinforcement	Health activities completed in quests and sparks (described in further detail below) mini games played Spa maintenance activities done, such as cleaning virtual environment	In-game rewards (experience points XP, increase in Spa rating, unlocking of areas and activities) out-of-game rewards (coupons to stores)
Negative reinforcement	Spa is neglected when a participant doesn't login for a while or hasn't done sparks or quests	Decrease in Spa rating
Intrinsic motivation/autonomy	Ability to select ways to earn rewards through games, virtual world cleaning, variety of quests and sparks that include many eating or physical exercise activities	Different rewards traded in for new game content
Visual feedback/competence	Choose from several visualizations of comparative performance of participants' progress against their friends or community Customize of game content (see below)	Changes in the appearance of the Spa, customized visualizations for showing performance
Social activities/relatedness	Ability to add friends and messages	Increase in cooperative and competitive activities

Fig. 12.2 Spark and quest interfaces

12.3.4 *Quests*

Quests are a thematic grouping of several tasks that typically take somewhere between a few days to a week to be completed. Example quests include, beginner training for biking, or planning a healthy meal outside with a friend. Quests take

Fig. 12.3 Avatar on running track in the game in response to data from pedometer

longer than sparks to complete, while they also reward more experience points. Players can track progress of their quests. Unlike, other similar commercial adventure or role-playing games (e.g. *World of Warcraft* or *Runescape*) quests in *Spa Play* cannot be shared. However, quest sharing is feigned through providing feedback on players' progress, showing quests that have been completed by their peers t and through offering options to finish a quest with a friend for earning additional experience points. Both *spark*s and quests are recurrent, repetitive activities that reward players with experience points to unlock new content for the island that improves the aesthetics of players' resort and its rating. Upon logging into the game, the game shows interesting statistical snapshots pertinent to player activity and progress in the game, such as showing how many *spark*s and quests they did the past week, each day, sparks done recently, and so on so forth. In short, the game is designed such that players may find motivation in being able to track what they did in the game [21, 33], while also finding the virtual island to be an appealing and persistent space to spend time in, maintain it and improve its aesthetics and rating (for example, see Figs. 12.2 and 12.3).

12.3.5 Player Profile Visualization and Real-Time Feedback from Activity Sensors

The game provides an elaborate interface for players to monitor their activity in the game. Several representations for feedback were designed as extrinsic rewards for intrinsically appealing activities. For instance, in-game material rewards are earned through completion of real-life activities. Continued feedbacks are also featured in forms of meaningful comparisons, using in-game material reward in addition to conventional charts or graphs (see Fig. 12.4). In all, the user profile visualizations sought to design a playful experience in self-monitoring and goal tracking activities. In addition, certain in-game events are triggered and driven by real-time data gathered by activity sensors. For instance, Fig. 12.3 is an image of an in-game running

Fig. 12.4 Player screenshots that show virtual rewards like *rainbow*, *flowers* used to decorate the island. The *chart* shows player progress in game in relation to other players

track with an NPC running. The amount of pedometer activity tracked by external activity sensors makes in-game NPCs to populate and run on the running track in the game—again, one of the many examples of the way in which the design is such that real-life activity improves the aesthetic appeal of the island; something akin to other similar social games, like *Farmville*, except that in the case of *SpaPlay*, rewards are earned mostly through doing exercise and eating nutritious food.

12.3.6 Social Play

Several studies also show that individuals' decisions about health, eating and exercising are influenced by their friendship-based and social networks [7, 22, 34, 35]. Thus, Spa Play incorporates friendship-networks through providing visualizations for player progress and tracking of individuals' and their peers' quests. For future development, the game seeks to leverage players' affiliation to their social and friendship circle in the game and their frequency of socialization (i.e. quests done with friends, use of visualization for comparisons, etc.) in making individually profiled recommendation for sparks and quests. Spa Play provides incentives for adding friends through different game mechanics. For instance, competition is promoted by providing comparative statistical visualization, while completing quest with a friend earns more rewards, thereby encouraging collaborative play (outside of the game). *SpaPlay* is not a multiplayer gaming platform; however, it provides multi-player in-game interfaces for interactions with other players via real-time chat and visualization of activities of players and their in-game social networks.

12.3.7 Participant Recruitment and Interviewing Methods

In spring of 2013, we designed and conducted a 45-day study to investigate acceptance of the health game—*SpaPlay*. The objectives of the pilot was to investigate how players perceived the game, which game design features and gameplay mechanics resonated the most with players, and to what extent did the game remain successful in relating to participants' daily regimen related to nutrition and physical activity. 18 undergraduate students participated in the study. Following an informed consent, participants filled out a baseline questionnaire that assessed their levels of physical activity, gaming and eating behaviors. All participants received instructions on accessing the game and were encouraged to play on a daily basis for a month. In-person interviews were conducted, once a week. Because of the semester break and scheduling difficulties, the study ran for the total period of 45 days. 16 out of 18 (88.88 %) participants played videogames at least 4–5 days a week.

6 out of 18 (22.22 %), reported exercising at a high intensity (i.e. breathing fast and cannot keep up with conversations; e.g. running, biking, playing soccer etc.) everyday or at least 4–5 times a week, while 10 of them (55.55 %) reported exercising hardly ever (or once a week). 2 out of 18 reported eating 3–6 servings of fruits and vegetables everyday, while the remaining (16 participants or 88.88 %) said they consumed 1 serving of fruits or vegetables everyday. In short, most the 18 participants (with a very few exceptions) seem to show an overall lack of attention to healthy eating and exercising routines in their daily regimen.

12.3.8 Game telemetry and Individualized In-Person Interviews

All players' interaction with the game was recorded in real time and is referred to as "game telemetry" [36]. We collected game telemetry data, which are player logs indicating player actions that are time-stamped (i.e. what players did or clicked and when it occured). These logs gave us indicators for what players did over time, including their login and out, the number and frequency of activities they did when they were logged in, number of quests and sparks they completed so on and so forth. The game telemetry was queried and the gameplay data was visualized for basic gaming activities, such as player leveling patterns, or quest completion times and frequencies (see Fig. 12.5). Such data, sometimes, gives a clearer sense of play patterns and activities, however, as mentioned by many researchers in El-Nasr et al. [36] it does not give us an indication of why players engage in certain activities and why they did not. In order to obtain a better context for the in-game telemetry data, we also conducted weekly 15-20 minute interviews with the participants of the study.

12.3.9 Telemetry-Based Individualized Interviews

A unique aspect in the methodology we used was formative and recurrent interviews that were customized for each player, weekly. Participants were interviewed after each week of game play. In this interview, the researcher asked them

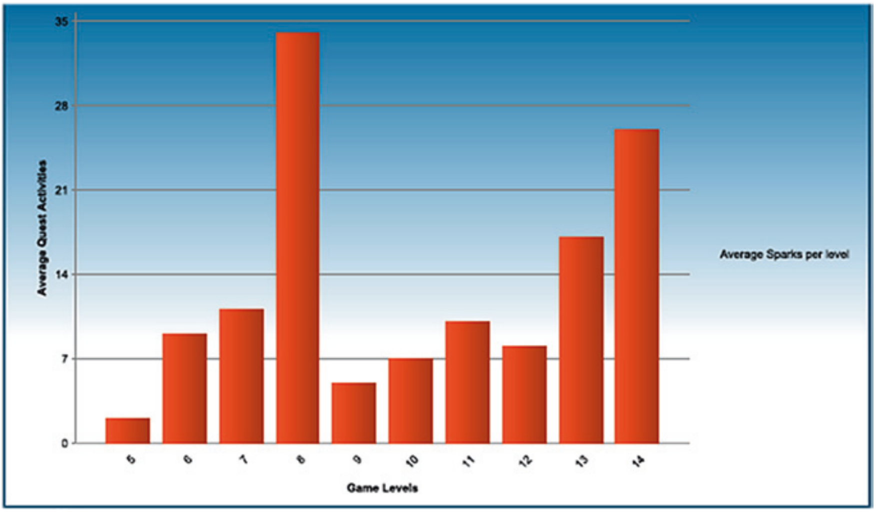

Fig. 12.5 Average number of quest activities amounting to XP at each level for all 18 players

about their impressions of the game. Our objective is to understand how useful or impactful players perceived the game metrics, and thus we sought recurrent in-depth game and play style characterizations in players descriptions of the game [37]. We used gameplay telemetry data that was visualized dynamically after each session to give us a clear indication of some of the play patterns. This data was then used to customize the interview questions for each player. We used three kinds of game-play characteristics to customize the interviews—player's leveling-up patterns, player's quest completion frequencies, and player's *spark* activity frequency. Interview questions were then modified according to how steep or progressive player's levelling-up has been, so as to encourage player responses that were relatable to their style of play and enthusiasm for the game. For instance, in cases where the player showed steady progression, some of the questions that were asked included: "do you think the game encourages you to explore new things or try new activities? How? If not, why?" Alternatively, players whose progression indicated steep increase in certain quests were questioned about the said spark or quest that they did most. For instance, questions such as, "what did you like about the spark—'use one slice of bread for sandwich'?" prompted participants to narrate what they perceived of healthy eating.

12.4 Findings

Overall, the key objectives of the study were to examine if the rewarding mechanics worked, to what extent did the game mechanics provide enough of an incentive for players to care about persisting in non-gaming activities, such as exercise or eating and, whether players were more keen on lingering in the virtual space, playing puzzles and other recreational games in the virtual spa. By doing so, we sought to provide prototypical caricatures of play in *SpaPlay* that helped determine the salient game metrics that are being captured by the telemetry, what they mean and how we might be able to study them in a larger scale (i.e. for future implementations of building automated interfaces that will infer simple patterns of play in a large set of data to help refine design). The findings section is divided into three broad categories based upon the gameplay mechanics and game features that are core to *SpaPlay*—Quests, Sparks and Perceptions about Game Island. Under each group, we report on quantitative findings from the game telemetry and complement it with emergent interview themes to help interpret what these findings mean.

12.4.1 Patterns Observed within Quests Completed by Participants

Using game telemetry data, the average of quest activities for all players was charted at each level. Figure 12.5 shows the distribution of experience points earned cumulatively at each level, totaled for all the 18 players in the study. As we can note, the experience points earned at earlier levels (like level 7 or 8) is higher and for latter levels the experience points tapered down. We inferred that the longer the players stayed in the game they seemed to level mostly through sparks, and explore fewer quests. A comparative distribution is presented in Fig. 12.6 showing leveling pattern with respect to sparks. As can be seen, and also explained again, players in the latter levels (like 13 or 15) earned most points through short-activities, or *sparks*, instead of longer, more planned *questing*.

In total, the average quest completion for all the players was found to be 18.8 (s.d. = 9.67, n = 505). Table 12.2 shows the breakdown of quests related to eating, physical activity and quests based on activities tending to the virtual island (like clearing the trash, harvesting, etc.).

Distribution of all the 505 quest-related activities completed by the players are listed in Table 12.2, grouped under food-related, physical activity-related or game-related. Food and physical activity related are self-explanatory. Game related quests were the ones that entailed completing certain tasks pertinent to the virtual island. Some examples of game-related quests include, "level till 7 to unlock banana trees", "harvest bananas", "visit the yoga studio", "find and visit the community lounge" and so on. Players spent a significant amount of time doing recurrent game activities that impacted their resort rating.

In addition, quest completion break down indicated that food-related quests were less frequently completed. Upon excerpting the interviews, we found that customization of quests based upon participant profile is crucial for player adherence to quests. Because the participants in this study were undergraduates, completing food related quests, such as following food recipes (e.g. Make

Table 12.2 Quest distribution

Quest related to	Number of times completed
Food	100 (19.8 %)
Physical activity	202 (40.0 %)
Game island	203 (40.19 %)

Cauliflower Mash) required more preparation, and hence were less likely to be picked up by the participants. At the same time quests that required minor adaptations with participants' lifestyles were more frequently picked up. Some of these quests include "Tame the Sugar Monster" quest that entails drinking water instead of sugary drinks for a week or "Eating out Healthy Portions" quest that entails eating half of a standard restaurant portion for a meal or packing ½ of it for later for a week.

12.4.2 Patterns Observed within Sparks Completed by Participants

Similarly, using game telemetry data, the average of spark activities for all players was charted at each level (see Fig. 12.6). The experience point distribution show that players completed fewer sparks in earlier levels, but mostly sparks in latter levels, as sparks became the most favored activity. We confirmed this through interviews as well.

Overall, sparks remained more popular than the quests. Sparks were found to be done at an average of 54.04 times (s.d. 70, range 0–80), and within 1 s.d. point from the mean, the 2 most popular sparks related to physical activity were "Lifting weights for 5 min", "Walk 10 min or walk with a friend" and "Ankle Rolls repeat 5 times". A more detailed break down of activity distribution along sparks has been included as an appendix (Appendix 1) at the end of the document. Similarly, the food related sparks were "Use 1 Slice of Bread for Sandwich" and "Eat ¼ Less for One Meal" and the 2 most popular sparks related to the game island were "Harvest bananas" and "Picking up Trash". On the other hand, sparks that rewarded playing mini games, such as puzzle games were less popular when compared to recurrent game-world activities, such as keeping your resort clean. In addition, we also found that game experience points from quests tapered as players progressed to higher levels, while experience points from sparks spiked as players progressed to higher levels in the game. In short, by comparing distributions from players *questing* and *sparking* activities (compare charts in Figs. 12.5 and 12.6), and through interviews we concluded that exploration in the earlier levels with quests or planned activities, like following a healthy recipe and preparing a new dish, tapered down to short-burst activities, like taking the stairs every now and then.

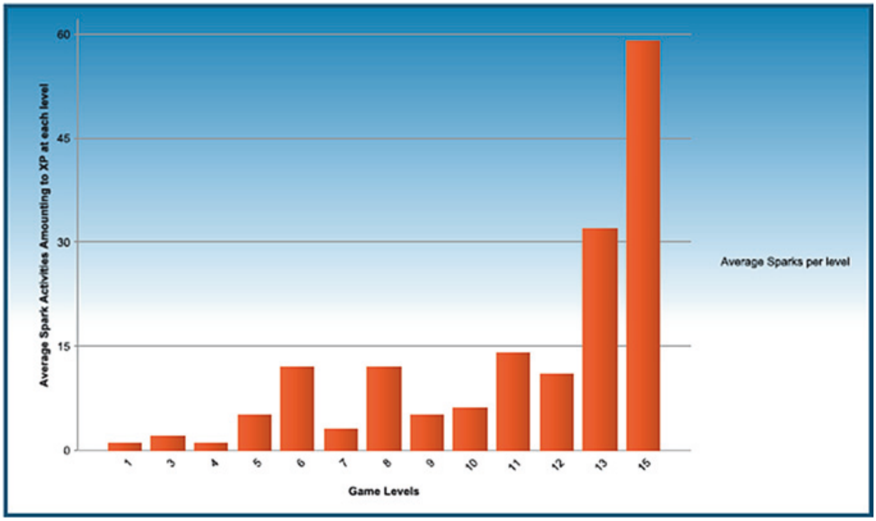

Fig. 12.6 Average number of spark activities amounting to XP at each level for all 18 players

12.4.3 Distribution of Player Game Activity

We also plotted frequency of player activity for each day of the study Figs. 12.7, 12.8 and 12.9 depict the distribution of *quests*, *sparks* and a comparison between the two respectively. As can be seen below the patterns of spark and quest distribution remain similar, while the levels of sparks remain higher than quests as can be seen in the line chart in Fig. 12.9.

This finding aligns with the leveling pattern for players (charts in Figs. 12.5 and 12.6), i.e. for the most part players tended to do more sparks, instead of planned quests, which suggested that after gaining a certain level of comfort with the game, players were less inclined to explore or continue doing goal-oriented tasks in the game. In other words, as players leveled higher, they seemed to repeat activities they normally tended to do and simply use the game as a checklist to level up with experience points accumulated through activities they did normally outside of the game.

12.4.4 Emergent Themes from Interviews and How they Explain Patterns from Game Telemetry

12.4.4.1 Importance of Being 'Honest' in the Game

One of the unanimous observations about the game made by the participants was the fact that the game relies on an "*honor code*". 17 out of 18 players ascribed to the fact that because this game is based on an honor-system and it felt like

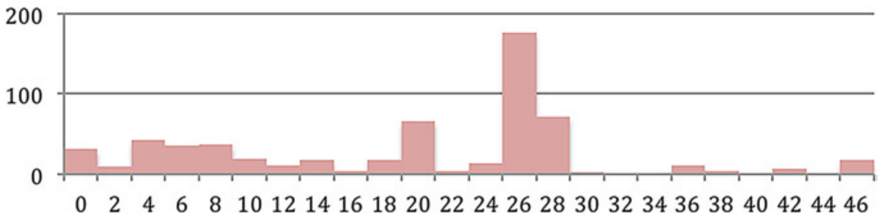

Fig. 12.7 Frequency of Quests for all players (n = 18) for each day of the activity

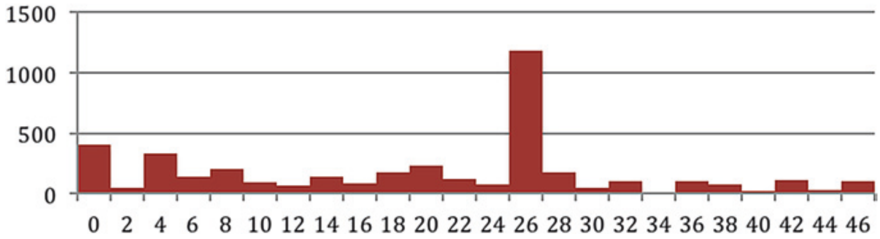

Fig. 12.8 Frequency of Sparks for all players (n = 18) for each day of the activity

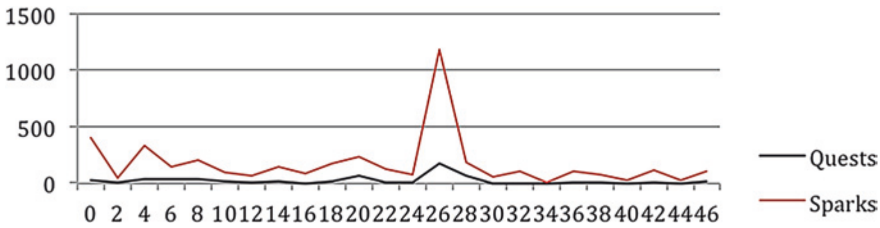

Fig. 12.9 Distribution of Sparks and Quests during the length of the study

cheating if they merely leveled-up in the game without actually doing the physical or food related activities, and instead, doing the island related activities, like cleaning the resort, harvesting the fruits etc to level-up. For instance, in the following excerpt, participant-005 uses the word 'honest' to describe his commitment to the game play.

> Participant-005: "I've been on the game at least once every day I think. I've done some of the activities, but sometimes they feel all redundant. But because, uh, I tried to keep myself **honest**—actually follow what they said to do in sparks, I tried to go on and update regularly"

12.4.4.2 Players Repeated only Those Tasks in Game that Fit Their Existing Routine

While the game was designed as a real-time activity tracker, with most of the activity *sparks* expected to be completed by the players when they were logged into the game, participants in the study used the game as an end-of-the-day checklist, checking from the choice of *sparks* in the game to denote that they had completed these activities during the day. As a result, the use of *quests* became less useful for the players. Consolvo et al. [21], note that in efficacy of use or the *stickiness* of a pervasive health technology tends to highly improve when users are empowered to set their own goals, track them and receive feedback on the progress they make. In other words, goal setting seems to be an important trigger for motivation in health games. However, through this study we found that *routinizing* seem to take precedence over planning and setting long-term goal. For instance, in the following excerpt the participant describes why and how repetitive tasks were useful, especially when they were aligned with his existing routine despite finding some of them somewhat redundant.

Interviewer: What would you say that is most appealing to you in this game?

Participant-005: I think that is a really good idea. Just because it is really hard to measure actually doing progressive healthy things, so the fact that they [the game] actually have a delimiter for doing x-amount of healthy things is a great idea.

I've done some of the activities, but then some of them seem to get redundant. I did them in a way that I could incorporate them into my **daily routine** better. So I picked the stairs one a lot because I live on the 4th floor. Going from the lowest one to the top one is like, almost impossible. But because there is this spark, I've tended to take them more.

Similarly, another player tried to incorporate the *sparks* as a way to continue some of their existing practices. In a way the game seemed to make players pay attention to the health-related choices they were making everyday. For instance in the following the player explains how she would play the game at the end of the day, spending time in the virtual island, tending to island-related activities and "check off" activities she may have done during the day. This helped her stick with her existing routine, while increasing her awareness about those activities during the day.

Interviewer: Could you walk me through what you'd start doing when you log in the game?

Participant-004: Yeah. So I log in, gather the coins and experience points you get for cleaning the resort and harvesting the banana trees; I'd get my runners [refers to the NPCs in the game] going and then I'll log any sparks that I did that day and then I'll usually play around for 15–20 min with the mini-games, like the word-runner puzzle game.

Interviewer: When do you typically log in?

Participant-004: I report the sparks at the end of the day. I can't log in during the middle of the day and so I go in at the end of the day. And they end up being the same ones every day. Because typically in the morning I'll take the bus to work, but like every day I'm able to check off the "get of one stop earlier one". That's something I did with my old job. Actually at that job I used get off like half a mile early and walk the rest of the way. Because that is something that I just kept up with in this job, everyday I can check off this spark.

In addition, existing routine far-outweighed the novelty in a spark or quest content. For instance in the following exchange, participant-002 reveals why he was interested in doing the sparks that he did.

Interviewer: Was there a favorite spark you had, that you ran across? or one that may be you felt is missing?

Participant-002: I wouldn't say that I found missing. some of the ones I like are the ones that just like—"you don't necessarily need to eat more or less of whatever, or

> exercise more or less of whatever". It's just, uhm, doing the same things you would do in a different way. Like, "eating dinner with a smaller plate", or "eating with your non-dominant hand" that kinds thing. That's just sort of like keeping up with your normal routine, but in a different way.

In this above exchange, participant-002 reveals points to an aspect of the game he particularly relates to positively, which is the game encourages small changes that are possibly an improvement on what one may normally follow as a part of their existing routine.

In comparison participant-004 in the following exchange finds the recipe-based quests that require more planning would work really well when they aligned to her weekly grocery shopping patterns.

> Participant-004: There are some quests that require, like more preparation on my part, which I haven't looked into and I would like to. Like some of the quests have to do with going out to eat, or cooking a certain way. But I can't complete those, because I haven't gone grocery shopping. But if I actually grocery shop, I would really want to start making these changes.

12.4.4.3 Player Perception on Rewarding Mechanisms

The game also seemed to impact player motivation through a negative reinforcement schedule. For instance, if the player logs in less frequently, the resort rating drops, and also poorly affects the aesthetic of the island—the island accumulates trash in certain parts, for instance. Some of these game mechanics that were recurrent and repetitive, but impacted negatively if the player failed to continue to do them seem to be a big motivator for the player to continue to come back. In one of the participant's own words—

> So, I think right now I am at level 12. I like where you kind of pick up trash to clean up your park, and I got the banana trees. I like that now there is more content [in the game], more of an incentive for me to log on more often and check. 'cause if I don't clean the trash up my resort rating drops to like 1–2 star or something

12.5 Discussion

In this chapter, we provide a detailed overview of the design considerations and some of the strategies that went into devising the reward mechanisms and activities that can sufficiently "infiltrate" players lifestyle [21]. Through a month and a half study investigating the game's acceptance, we noted several salient findings regarding efficacy of the design of reward systems in *SpaPlay*, overall patterns of activity in the game and player motivation to continue playing *SpaPlay*. First, in terms of game mechanics, both *quests* and *sparks* seemed to remain fairly relatable to participants. As the findings suggest, rewards for repetitive activities was something that was of value to players in this study.

Players' propensity to set goals—something that several other studies on ubiquitous technologies for health have also argued about—is an important metric for success of pervasive technologies, albeit this is a complex aspect of design. In *SpaPlay*, because the game actions for leveling up are much open-ended, players were more likely to repeat actions that seemed to align with their existing routine. However, the activity patterns did indicate that soon, players become comfortable with a narrower set of routines and continue to use those as their primary actions in the game to level up or progress in the game. As has been accounted for earlier, in the initial levels of the game, players accumulated most of the experience points from questing activities that required more prior planning, whereas, in comparison to later levels, most of the leveling was through sparks or short-burst, instantaneous activities. This led us to infer that players start exploring elaborate quests, but once they find a narrow set of activities they find suited to their lifestyle, use them as the primary means to progress in the game.

Second, we also found that recurrent *grinding* activities, such as keeping the resort clean, and experience points that kept opening new game content to improve the aesthetics of the virtual island were strong motivators for players to continue to log in their daily eating choices and physical activities. The game in its current state remains limited in its capacity to incentivize "exploration", or give players the extra push to do new activities.

Third, we also found that adherence to games like *SpaPlay* is more likely to improve if the content of the game lends to adoption into the daily fabric of participants' life, and hence, could greatly benefit from *adaptive messaging* or profile-based game content [38, 39]. For instance, findings from the current work indicate that an open-ended gaming environment remains well suited for catering to a spectrum of participant profiles, offering participants with choices they could stick to in their routine. However, this means improving personalization and customizability of game content. For instance, one of the findings from the breakdown of quest content is that this particular group of participants completed the food-related quests which required more effort with much less frequency, e.g., recipe based quests. Nonetheless, participants did seem to be interested in doing recipe related quests if they had been more aligned with their living style, such as leaving longer time frame for completion so that they had time to prepare. In short, while we found that the quest content in *SpaPlay* were relatable to the players and had the potential to generate player interest, varying and adding new quests also makes the game a moving target—complex system with inter-related and changing variables. Thus, an instrumented game provided both researchers and designers an interface to experiment with inventive approaches that can continue to influence player activities outside of the game [40].

Finally, open-ended gaming systems for health, like *SpaPlay,* face a complex design challenge in terms of customizability. As can be seen from the findings reported in this chapter, players tended to repurpose the game to suit their existing needs. What this implies is that while the game has a promise to bring about and strengthen a sense of awareness towards day-to-day healthy routines, we also want to be cautious of the risk of monotony (e.g. players sticking to sparks instead of elaborate quests, at higher levels). In some ways, success for games like *SpaPlay* is contingent upon the "buy-in" that the players can relate to [41] in order to feel encouraged to look at the "other" healthy things they could be doing in the game. Players described their participation in terms of "reporting back to the game" and "keeping oneself honest". Such findings seem to suggest that while experimental techniques play a role in evaluating the health benefits from participation in health games in the immediate run, much like testing a feature or the impact of a technology, theory-driven approaches are needed to better depict longitudinal health-behavior change [11]. As [42] has, elsewhere, argued that there is a need for a health lifestyle theory and that when it comes to health behavior change, structural dimensions of daily lifestyle significantly impact health outcomes. When designing sustainable technologies for longitudinal health benefits, it is critical that "collective patterns of health-related behavior based on choices from options available to people" ([42], p. 55) be studied so as to leverage technology to influence some of these patterns. Our study, thus far, seems to suggest that open ended and flexible platforms, like *SpaPlay* have the potential to give designers the tools necessary to progressively modify design metrics so as to suit players' collective patterns of health-related behavior.

12.6 Conclusions and Implications for Future Work

Research in health and personal health management have changed in crucial ways, particularly moving away from a diagnostic and an interventionist models to designing formative, feedback-oriented and longitudinal models for long-term health behavior change. When it comes to designing tools to sustain player adherence in activities related to health, it is important that we understand how and to what extent rewards and incentives in the game are *persuasive* and compelling to entice players in adhering to the game over time; in the case of *SpaPlay* adherence constitutes performing sparks and quests related to physical activity and eating. In conclusion, some of the implications for future work involve refining the design metrics that can improve adherence in ways that can push players to go beyond their existing lifestyle choices. In addition, because the work presented in this chapter is largely descriptive, our ongoing efforts are in the direction of designing tools, like visual querying interface to observe players' collective health-behavior, which can facilitate decision-making at the designers end to include or leave out certain game content.

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Part III
Applications in Neuropsychology

Chapter 13
Virtual Reality for Neuropsychological Assessment

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Abstract Neuropsychology comprises a set of theoretical and experimental knowledge about relationships between the brain, cognitive processes and human activity. However, in the latest years, several criticism have been raised about the validity of neuropsychological tests for capturing nervous system dysfunctions and predicting the level of decline that individuals may show in their daily lives. Traditional paper and pencil tests lack ecological validity and generalizing its results to describe daily life cognitive functioning of individuals is controversial. In order to overcome this, and in parallel with development and cost decreases of virtual reality (VR) technology, integration of informatics and neuroscience is approaching the achievement of a more objective, precise, and ecologically valid neuropsychological assessment based on VR technology. The current chapter describes the problems faced with classical neuropsychological assessment tools and the need of improvement of their validity; the potential advantages of using VR based neuropsychological tests versus classical tests; and the actual progress made in using VR based tools to measure cognitive functions such as attention, memory or executive functions, with some of these tools already standardized and available in the market. Finally, predicted advantages of these tools for the early diagnosis of different neurological and neurodegenerative conditions and its implications in reduction of healthcare costs are considered.

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List of Acronyms

3D	Three-dimensional
AD	Alzheimer’s disease
ADHD	Attention deficit hyperactivity disorder
CPT	Continuous performance test
CVLT	California verbal learning test
LFAM	Look for a match test
MCI	Mild cognitive impairment
TBI	Traumatic brain injury
RBMT	Rivermead behavioral memory test
V-STORE	Virtual store test
VAPS	Virtual action planning supermarket
V-MALL	Virtual mall
V-MET	Virtual multiple errands test
VR	Virtual reality
WCST	Wisconsin card sorting test
WISC	Wechsler intelligence scales for children
WISC-R	Wechsler intelligence scales for children—revised

13.1 Introduction

As a scientific discipline within neuroscience, neuropsychology comprises a set of theoretical and experimental knowledge about relationships between the brain, cognitive processes and human activity. In its applied variant, clinical neuropsychology is devoted to identify, describe, evaluate, diagnose and rehabilitate cognitive, behavioural and emotional disorders derived from dysfunctions of the central nervous system. In addition, it evaluates the impact of those dysfunctions in people’s social, working, family and personal environment, as well as the evolution and benefits obtained from the implementation of intervention programmes. Finally, clinical neuropsychology must establish clinical and legal consequences derived from each individual case. In order to fulfil that purpose, multiple tools are used, such as direct observation, interviews, scales, questionnaires and neuropsychological tests, all of them allow measuring performance of individuals both from a quantitative and a qualitative point of view.

In the latest years, neuropsychological assessment has been the target of several criticisms from some groups of professionals who assert that tests are lacking any kind of validity both for capturing nervous system dysfunctions and predicting the level of decline individuals may show in their daily lives. However, neuropsychological tests must be understood as tools founded on a theoretical justification with regards to their reliability and validity, and carefully prepared to elicit behaviours of an individual. The goal is to derive the knowledge about cognitive processes underlying elicited behaviours, and the relationship between these behaviours and its role in the daily life of that individual.

In expert hands, neuropsychological tests comprise a high diagnostic value, a value which is lost if the person does not know about neuropsychology, does not have a theoretical model to describe cognitive processes, or just focuses on test scores thus ignoring the processes that led to those results. However, even if these requirements are met, many neuropsychological tests are based on experimental paradigms so artificial (for example, learning associated pairs) that obtained results lack value when it comes to predict how that person will behave in his daily life. In classical neuropsychological assessment, it is very frequent that the subject is presented with tasks to be performed in the evaluation setting, but generalization of these tasks to the rest of that person's daily life is quite controversial. One of the reasons is that the evaluation setting itself (health care centre, office) is a strange environment for many populations, for example, people with intellectual disability [34]. Additionally, as many authors state [2, 24, 30], they try to evaluate pure aspects of memory (for example, visual memory). Moreover, classical evaluation tests are conditioned by a floor or ceiling effect, tend to evaluate the information storage in a relatively brief period of time (20 min), and demand learning of information which does not have any personal relevance for the patient. Finally, the classical evaluation environment is closer to a "lab environment" and thus lacks contextual cues the patient may benefit from in their daily life environment; in addition, distractors are minimized, sensorial modalities are not mixed, and environmental conditions (noise, temperature) are maintained equal to everyone, a situation that is far away from real environment demands. In sum, traditional tests do not reproduce the wide range of stimuli a subject may encounter in his daily life.

The most innovative trend in neuropsychological assessment is focused in developing new instruments that explore behaviours and activities similar to the features of the natural environment in which patients' daily life usually takes place. The search for a higher ecological validity has led in the last decades to very diverse initiatives to evaluate cognitive functions in real life situations. Ecological validity refers to the degree to which a procedure reproduces or approximates to the real capacity that it intends to predict. For example, if the intention is to determine the driving ability of somebody, its performance in a driving simulator has more ecological validity than its performance on a paper-and-pencil test about driving knowledge. Other examples of ecologic versus non-ecologic could be memorizing a shopping list versus a list of randomly selected words; recognizing faces versus senseless shapes; or counting coins versus performing arithmetic calculations. According to Lynch [29], some tests are presented as ecological while there is no description about the criteria followed to increase their ecological validity, while some tests contain tasks that are mere transformations of tasks performed in other tests [50, 58].

Due to the series of problems with classical neuropsychological tests presented above, attempts to develop new forms of measuring cognitive functions have been developed in the latest years. Currently, new technological developments in the field of virtual reality (VR) offer novel and interesting options in the neuropsychological evaluation of many cognitive processes. VR reproduces three-dimensional (3D) environments in which the examined person interacts in a dynamic way, with a sense of immersion in that environment similar to the presence and exposure to a real environment [10]. Within these environments, both researchers and clinicians may present the most ecologically relevant stimuli integrated to a significant and familiar context, and thus measure the response in a more exhaustive way (as long as the visual and physical features of depicted characters and items show high quality and are realistic). Moreover, VR technology allows synchronization and control over distractors, stimuli, variables, and can alter all those depending on the response features of the patient. Answers are more accurate and consistent, and may allow a more precise and detailed analysis.

According to Tarr and Warren [52], though initially the technology development was small and costs were high, VR has finally returned to the necessary maturity for its application in neuroscience. Nowadays, any medium range computer may display an immersive, interactive virtual environment, and increase on performance has run in parallel with decrease in costs. As Riva et al. [42] state, VR provides a new paradigm of human-computer interaction in which users are not mere external observers of images in a computer screen, but active participants inside a computer generated virtual 3D world. Rizzo et al. [45] identify different advantages which are available thanks to the use of virtual reality in neuropsychological tools. Among those, the most relevant for neuropsychological evaluation are the following:

1. Ability to systematically show dynamic and interactive 3D stimuli within a virtual environment, a job that otherwise would be difficult to perform using other means.
2. Ability to create an evaluation environment with greater ecological validity.
3. Presentation of immediate performance feedbacks in a variety of forms and sensorial modalities.
4. Ability to completely capture the performance and availability of a more naturalistic and intuitive registry of performance for the posterior data analysis.
5. Design of a safe evaluation environment that minimizes risks derived from errors.
6. Ability to improve the availability of evaluation for people with sensory and motor decline by means of the use of adapted interfaces and devices, and presentations adapted to the required sensorial modality and integrated in the design of the virtual environment.
7. Introduction of "recreational" features or elements within virtual environments as a means to increase motivation.
8. Integration of human virtual representations (avatars) for systematic applications that may enhance social interaction.

Rizzo et al. [45] conclude that, though VR is not the panacea for any type of behavioural analysis, it represents a great opportunity in terms of usability and usefulness in the neuropsychology area, and one of its great advantages is that it is considered to have a high ecological validity. The higher its ecological validity, the better the test can predict the problems or limitations a person may present in its daily life. In summary, if the correlation is high between the answer of a patient who is undergoing a test to measure performance in a concrete real situation, and the answer that this patient provides in real daily life, it can be said that the test is actually measuring the behaviour this individual would have in real daily life when faced with that situation [20]. Obviously, the establishment of such a correlation would require the comparison of test results with subjects' performance in their daily lives; a study which is very difficult to perform in real daily life.

For that reason, many authors compared results obtained in classical tests and simulated VR environments in order to offer ecological validity. As we will see, there are many examples of virtual environments that illustrate real life environments in order to obtain ecological validity in assessment and rehabilitation procedures: virtual cities [8, 15], supermarkets [12]; homes [46]; kitchens [9, 16]; schools [49]; offices [31, 48]; rehabilitation units [6] and even a virtual beach [19]. Interestingly, lately VR has also been considered a reliable method to test Attention Deficit Hyperactivity Disorder (ADHD) children's ability to sustain performances over time, especially by the research team of Rizzo and their *Virtual Classroom* [4, 43]; and lately by different research teams in Spain based on the *AULA* test developed by the company Nesplora Ltd. [10, 17, 22], which will be described in the next section.

13.2 Neuropsychological Tests Using Virtual Reality

Below, we described precisely the contribution of virtual reality technology to the development of innovative tools in the field of neuropsychological evaluation. History of neuropsychological tests which use virtual reality environments will be presented, providing with details from those tests who just were direct transfers to a computer environment of a paper-and-pencil test (thus lacking ecological validity) to the latest scientifically validated developments (some of them, already commercialized) in neuropsychological testing, specially for attention, memory and executive functions. Both obtained advantages and existing limitations that will require further research and validation work will be remarked.

13.2.1 Attention

Tests that are used to measure attention are a matter of controversy. As Zomeren and Brower state in Lezak et al. [28], there is not such a thing that can be called attention test, you can only evaluate certain aspects of human behaviour putting special interest in attentional aspects. Attention is affected in many cerebral disorders, being these either evolutive, or traumatic or degenerative. We talk about attention when we measure reaction times, vigilance, immediate memory, processing speed and mental control, and it has been usually measured with paper-and-pencil tasks such as cancellation tasks, or trail making tests, involving attention and visual perception, or auditory tasks to involve auditory attention.

Probably, the most typical case of attention problems is related to Attention Deficit Hyperactivity Disorder (ADHD). ADHD is a neurobehavioral developmental disorder with a prevalence of 5–7 % in population below 19 years-old, though in the latest years the diagnosis in adults is increasing. This disorder creates problems to children in school age since it affects concentration and learning. Its diagnosis is complex, requires a clinical evaluation done by a specialist, usually a neuropsychologist, and information must be obtained both from direct observation of child's behaviour as from information provided by parents, teachers and other relatives. One series of tests used to psychometrically measuring children attention are the so-called *Continuous Performance Tests* (CPT). These tests have evolved from paper and pencil to simple computer programs that require answering to a concrete stimulus pressing a key.

Faced with this reality, Rizzo et al. [44] had the idea of developing a VR application for the evaluation of ADHD in a three-dimensional virtual classroom, in which the child gets immersed to perform a task appearing in the blackboard. The child interacts with the environment thanks to a stereoscopic headset with a movement tracker (*eMagin z800*), so that when the child move this head, the vision of the virtual environment moves accordingly. This system presents the following advantages:

1. A greater ecological validity for evaluating ADHD, as the subject is faced with a situation more similar to reality when compared to classical tests and interviews with parents and teacher. The greater ecological validity has not been directly proved, as it is not feasible to measure the child's behaviour in a real classroom and compare the performance with a virtual classroom, but the resemblance is quite obvious.
2. It allows configuring the presentation of both auditory and visual stimuli in a systematic way. The software allows the presentation of 20 different distractors (for example, a car passing by in the street, the janitor coming into the classroom and other typical distractors of a school classroom) that appear while the child performs the task appearing in the blackboard.
3. With regards to data collection, the virtual classroom analyzes the child's answers to the task (reaction time, variability of reaction time and performance with commission and omission errors), apart of storing head, arm and leg movements with sensors (to quantify hyperactivity). With these data it can be inferred when and how distractors will affect the subject's performance, an attention deficit can be evaluated but also an effective and personalized treatment for every child can be designed.

Three years later, the same team performed another study with the same virtual classroom. In this work [35] results obtained in 2004 were replicated, finding that the group with ADHD made more omissions, commission and greater body motor activity than the control group, and the performance of participants with ADHD was more affected by distractors. Results were also compared with a battery of classical neuropsychological tests, and it was found that measures obtained by Virtual Classroom correlated with classical instruments, information about motor activity in an objective manner was provided, and a distractor-dependent cognitive profile was obtained, concluding that VR could provide concrete and objective data beyond the possibilities of classical tests in the evaluation of ADHD subtypes. Adams et al. [1] confirmed better discrimination abilities for Virtual Classroom when compared to standard CPTs.

In 2002, Lengenfelder et al. [27] made a research about the performance of people with brain injury in attention tasks. The virtual environment used consisted of a driving course, where the main task was "driving a car" and the secondary task was the correct identification of 4 numeric digits presented during the driving lesson. The numbers were presented in the windshield of the vehicle. The stimuli presentation rate varied (2.4 vs. 0.6 ms) to differentiate divided attention. Results suggested that participants with a brain injury had higher difficulties to complete the secondary task when compared to healthy controls. Hence, both Rizzo's Virtual Classroom and Lengenfelder's Driving Course provide two feasible options for the use of virtual reality to evaluate attention in healthy and clinical populations.

In this context, one of the most promising tools is the virtual reality based neuropsychological test developed by the company Nesplora, the AULA test [10]. AULA (Classroom, in Spanish) is a computerized CPT which is performed in a virtual environment and designed to evaluate attention processes and support the diagnosis of attention disorders. The AULA test is directed to children from 6 to 16 years-old. It analyzes the child's behaviour within a virtual school classroom shown through a set of 3D glasses with earphones and head movement trackers. The software updates the perspective based on the head movements, providing the user with the sense of actually being inside the classroom. By means of the virtual blackboard and the earphones, a series of stimuli are displayed and the patient has to answer according to the instructions presented (Fig. 13.1).

The test comprises two evaluation exercises. In the first one, the child must press the switch whenever the presented stimulus is different form the target stimulus (No-X paradigm, related to impulsivity). In the second one, the child must press the switch whenever he/she hears or sees the target stimulus (X paradigm, related to inattention). The test, apart from presenting a high ecological validity, has the advantage of being perceived as a game in which there is a need to perform a task which combines visual and auditory stimuli, thus providing with more diagnostic information than unimodal CPTs [18] and which includes real life distractors—the teacher walking around, a car passing by in the outside, two students exchanging notes, someone talking in the back side, someone coughing, etc.—whose presence in computerized CPT is low [11, 54]. It offers scores about: sustained attention, divided attention (visual and auditory); impulsivity; excessive motor activity (hyperactivity); tendency to distraction, and processing speed.

Once the test administration finalizes, AULA provides with data about correct answers, omissions, commissions, response speed, and variability in response speed. Moreover, movement sensors placed in the 3D glasses allow counting the number of occasions a child has deviated the attention focus. It is also possible to compare the performance with and without distractors, compare performance between NO-X and X task, or how people perform in terms of visual versus auditory attention. The normative study of AULA with general population of Spain has been recently published in Journal of Attention Disorders [22], and recently,

Fig. 13.1 Screenshot of AULA Nesplora

the convergent validity with Conners' Continuous Performance Test has been published in Child Neuropsychology journal [17].

13.2.2 Spatial Attention: Hemineglect

One of the neurological problems most studied by means of VR (both with regards to assessment and rehabilitation) is spatial hemineglect. This phenomenon is presented after a cerebrovascular accident or a traumatic brain injury and implies inattention or failure to respond to stimuli appearing in the contralateral side of the injured brain hemisphere [56]. Normally, the evaluation of this disorder is performed using paper-and-pencil methods, or by means of a clinical evaluation of patients and relatives, as when it is observed that the patient forgets tying the left shoe [3], shaving half of the face, or cutting nails of the unattended side. With paper and pencil tasks, inattention is studied by line bisection tests (the patient must mark the central part of the total line, patients who neglect their left side mark the centre of the line in a point significantly deviated to the right side), cancellation tasks (in which the patient will not mark the elements or items placed in the left side of the paper) and copies of drawing in which a part of the drawing is omitted (for example, a clock with only a half of the sphere or a flower lacking

Fig. 13.2 Virtual street-crossing environment [56] (used with permission)

half of the petals). Treatment is focused in making the patient pay attention to the neglected side, provoke contralateral side exploration tasks, visual motor tasks, etc. When it comes to virtual reality, Weiss et al. [56] obtained conclusive results on the effectiveness of VR in the treatment of this disorder, reaching to the following conclusions:

1. In the same VR task of crossing the street with stimuli at both sides of the avatar that represents the patient, the control group needs less trials to reach higher levels, with less time to cross and less accidents, having to check the traffic less than patients.
2. Patients with hemineglect present significant differences in their deviation angle, reaction time to visual and auditory stimuli [23], and would benefit from the treatment if the asymmetry between the results of these variables in the right and left side are decreased (Fig. 13.2).
3. With a virtual reality task, it would be possible to evaluate the deficit quantitatively but also its differentiation with respect to hemianopsia (lack of vision in one side) and it would probably provide more information about the mechanism of the disorder and about the difference of neglect focused on the object versus neglect focused on the task [3].

In summary, it seems that VR tasks designed to evaluate and treat this kind of neuropsychological disorder have provided good results. The advantage is that quantitative calibration of neglect using virtual reality can be evaluated objectively [23]. A good example of VR systems providing high immersion is the Gesture Xtreme VR system, which uses computer vision for gesture recognition [56].

Since these systems are increasingly affordable for rehabilitation clinics, these skills can be trained with virtual reality scenarios: one common goal is providing the patient with a higher independence increasing his safety or control in the neglected side, either diminishing discrepancy between left and right side, compensating the loss of attention towards the contralateral side, or also training patients in virtual scenarios to increase their consciousness and attention. Current scenarios provide the patients with the chance to use their residual functional motor and cognitive capacities. The virtual street crossing scenario is also being used to rehabilitate patients with generalized attention, spatial perception problems or older people who have suffered a hip fracture [56], and is currently undergoing a controlled clinical trial to capacitate patients with stroke in right hemisphere and lateral neglect to improve their attention and increase their ability to "retain or track" left side images.

13.2.3 Learning and Memory

Memory implies a complex system by means of which an organism registers, stores, preserves and retrieves certain exposition to an event experienced previously. Normally, memory assessment includes immediate memory, learning in terms of recent memory, learning abilities, ability to preserve recently learned material and efficacy in retrieving information acquired at a short and long term [28].

Memory can undergo an assessment by means of verbal or visual tools, and differences may take place depending on the nature of brain injury or pathology. Memory and learning can be measured with specific tests (such as Rey Auditory Verbal Learning Tests Word lists, California Verbal Learning Test—CVLT, Store Learning Incidental Learning or Complex Figure Test), with memory assessment batteries (Wechsler Memory Scale) or within more complex assessment protocols are those oriented to measure executive functions.

With regards to ecological evaluation of memory by means of virtual reality, all examples come from research. One of them is the *Virtual Reality Cognitive Performance Assessment Test* (VRCPAT), developed at the University of Southern California by Parsons and Rizzo [36]. It is a measure of learning and memory using a virtual city environment to evaluate memory of certain places or target stimuli spread around a city with people of all ages and genders, a market, parked cards, animals, buildings, traffic signals and a series of objects (trash containers, wooden barrels, etc.). In 15 min, there is a first stage of acquisition of items in a verbal out-of-context manner, for subsequently getting immersed in the virtual city. In this context, the user must move from one target-zone to the next one, having to recognize in each zone 2 of the previously verbally presented items; once they are found, they have to align the spotlight with the object and click a button to collect them. Time lapsed in each target zone is 1 min at the most; if the user needs less time, he must wait until the time ends to go to the next zone; if the minute passes without having found the objects, an alarm rounds and a voice tells the user to move to the next zone and to search the two objects located there. In order to avoid guessing by pressing the button with every object they find, subjects are indicated that they can only press the button twice in each target zone. In the final round, subjects are asked to remember the original stimuli list and in which zone they were found. Measures of performance provided by this test include number of correct answers, number of errors, time required to successfully complete each target-zone, and total performance time.

Previously, Knight et al. [25] had developed a virtual city taking pictures of 1,400 places of inner and outer spaces of all shops of a mall in the north of New Zealand, and, using Microsoft FrontPage they connected the pictured and inserted background sounds such as traffic noises or walking steps.

The participant may move on this virtual environment across the street and enter different stores pressing various buttons on a navigation bar. For their study in 2006, they divided the street in 2 halves, one of low and one of high distraction (with more visual and auditory noise). It was tested in 20 people with TBI (7 severe, 7 very severe and 6 extremely severe) and 20 paired controls, who completed both a permanent task and a prospective memory task while they "walked around the street". In the permanent task, they had to complete 10 errands with a list that was accessible all the time. The prospective component required to answer to three goals that appeared repeatedly. As predicted, TBI group performed worse than controls in both tasks and were more vulnerable to distractors. These results suggest that daily life deficits in memory abilities in people with TBI can be more obvious when remembering implies executive processes, and computer-based VR simulations may help to construct sensitive measures of these memory abilities in daily life. Matheis et al. [30] using a VR environment to evaluate learning of 16 objects appearing in a virtual office, showed that VR test distinguished quite precisely between users with TBI and controls; moreover, the test correlated with CVLT, thus showing high construct validity.

13.3 Prospective Memory Evaluation

As both Knight and Titov [24] point out, the use of VR for measuring prospective memory is feasible. A comprehensive evaluation must include different types of "retrieval opportunities" described in literature [7]. These opportunities are event-, time- and activity-based. Event-based tasks required an action in response to a key (for example, to remember a message when you see a friend; time-based tasks required an action in a future moment specified previously (for example, to have an appointment at 3 p.m.); and activity-based tasks required an action before or after performing another one (for example, turning off the oven after cooking). Based in this classification, evaluation of prospective memory should include a series of instances for each of these retrieval tasks. As Brooks et al. [7] state, such an evaluation of daily life events is not feasible in real settings, but could be performed using Virtual Reality environment. In their study, they used a four room virtual bungalow to evaluate the memory skills of stroke patients and age-matched controls to perform event, time and activity-based prospective memory tasks, while they were involved in a task of removing furniture.

The event-based task implied remembering putting a sticker with the world "fragile" in 5 crystal items prior to moving them; time-based task was to allow the removal company to access at exact 5-min intervals; activity-based task implied keeping the kitchen door close to prevent the cat from escaping. As a comparative measure, the Rivermead Behavioral Memory Test (RBMT) was used.

A relevant finding was that 17 out of 42 stroke patients and 29 controls were unable to remember all the instructions of the three prospective memory tasks once they had removed the furniture, though they had been able to do it before performing that duty. As authors point, if an ictus patient cannot remember what to do, it is very unlikely that he remembers when to do it, an issue that needs to be remembered by rehabilitation professionals. The main result was the remaining ictus patients failed in the 3 prospective memory tasks, though they failed less in time-based task, which may require further research increasing intervals. In addition, patients with stroke did not show differences with regards to controls in the RBMT test, indicating that VR based assessment is more sensitive to prospective memory decline than classical tests (while Rivermead only contains one prospective memory item, this VR task include from 3 to 6 retrieval opportunities). More recently, Sweeney et al. [51] developed a Virtual Warehouse in which the user had to pick up furniture and deliver it in a house with 7 different rooms (hall, dining-room, medical-kit room, kitchen, studio, music room and bedroom) with no time limit and measuring their performance when presented with different event, time and activity-based retrieval opportunities.

13.4 Spatial Orientation and Spatial Memory Evaluation

There are not many studies in spatial orientation based on virtual reality. The most representative one is the one in which Cushman et al. [14] compared the performance of patients with Alzheimer's disease, Mild Cognitive Impairment and controls (younger and older) on a real hospital route and compared it with its exact replication on a virtual environment. They concluded that the virtual environment is a valid navigation test to observe topographic disorientation, as decline or lack of decline observed in the real route was also manifested in the same parameters the virtual route. They suggested that people create cognitive maps when they move in a virtual environment, equal to those deployed when exploring a real environment, and that virtual environments may serve to detect navigation problems, keeping in mind that performance in the virtual environment was somewhat inferior for all studied groups. With regards to spatial memory, tools developed by Morganti et al. [33] are fair representative examples of VR-based neuropsychological assessment.

VR-Maze and VR-Road Map

Morganti et al. [33] developed two VR tests to evaluate topographical disorientation secondary to acquired brain injury in parietal, temporal, occipital areas:

- VR-Maze test, based on the WISC-R maze subtest. Patients were asked first to perform an allocentric version on paper (i.e. watching the whole maze from the outside) of 8 mazes, to memorize them and then to try finding the equivalent egocentric (i.e. first-person view) in the virtual reality environment. Time lapses for each maze were registered (Fig. 13.3).

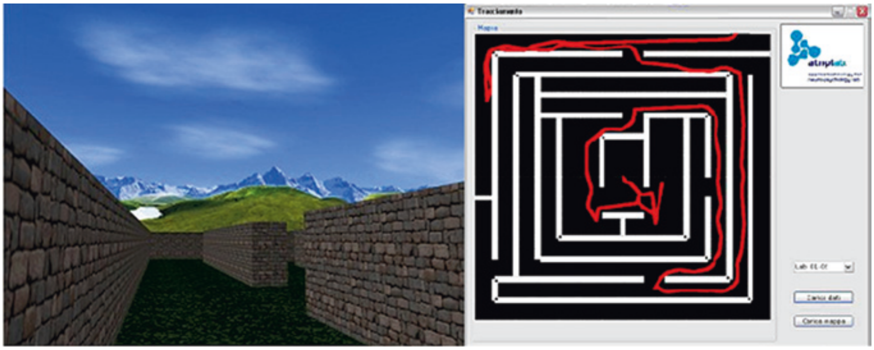

Fig. 13.3 Virtual Maze [33] (used with permission)

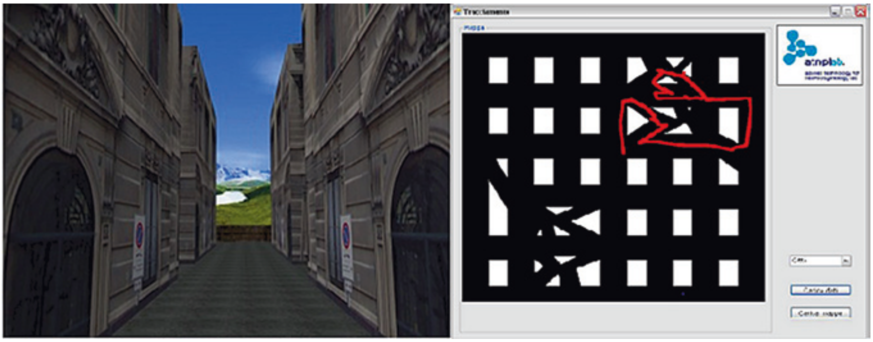

Fig. 13.4 Virtual Roadmap test [33] (used with permission)

- VR-Road Map test, a virtual reality version of Road Map Test [32] in which paper-and-pencil version is transformed into a simulated and actively explorable city. No cues were provided and all the buildings have the same texture. Patients were asked to follow the specified route using a previously performed paper-and-pencil version as a map. Time and errors were registered. In both tests, as shown in figures, routes performed by patients were registered.

The sample of the study was small (only 4 patients with TBI and 10 controls). In VR Maze, patients were significantly slower and resolved only 4 out of 8 mazes. In VR-Road test, while controls showed no difficulties, patients were slower and none of them could finish the itinerary. Sample size and lack of standardization were the main problems, but however this study shows how EV can be an efficient means to measure topographic memory.

As it has been presented, use of VR environments—especially mazes—to study spatial memory is one of the most frequent uses in neuroscience research. Other examples include the Virtual Park and Virtual maze of Weniger et al. [57], Virtual mazes of Bohbot et al. [5], and Memory Island Test [37] (Fig. 13.4).

13.5 Episodic Memory Evaluation

According to Plancher et al. [38, 39], most of episodic memory neuropsychological evaluations are unrelated with events that patients may experiment as real memories in their daily lives. This group was the first in using a VR environment to characterize episodic memory profiles in an ecological way, which includes memory for central and perceptual details, spatial-temporal context elements, and fixations. Subjects from three different populations were included: healthy older adults, patients with amnesic Mild Cognitive Impairment (MCI) and patients with mild to moderate Alzheimer's Disease (AD). Authors tried to determine whether environmental factors that may affect coding (active versus passive exploration) have an influence in memory performance that takes place in pathological ageing. Third, they compared VR episodic memory test results with a classical memory test and a subjective memory complaints scale. For this purpose, patients were immersed in 2 consecutive virtual environments; first, as drivers in a virtual car (active exploration) and second, as passengers of this car (passive exploration). Subjects were instructed to code all the elements of the environment, as well as associated spatial-temporal contexts. After each immersion, recall and recognition of central elements (i.e. environment elements), contextual information (temporal, egocentric and allocentric information) and quality of fixation were evaluated. Users underwent initially 2 training sessions (in both active and passive modalities) in order to get familiarized with VR and the virtual car (Fig. 13.5).

In the test, active participants navigated across a simple route of 10 turns. Participants were instructed to drive in the city centre, not Shopping and memorizing all the elements of scenes they might find within that environment. In addition, they were asked to remember details, specifically, temporal and spatial context details. Passive drivers received the same instructions. In order to match active and passive conditions, each active itinerary was recorded and presented to other participants in the same group as a passive itinerary. Thus, passive participants only saw the video and did not drive nor decided the itinerary. Right after the immersion, participants performed recall and recognition tests to evaluate their episodic memory, and then they were exposed to the counterpart of the first immersion (active users were now passive, and viceversa). Results showed that allocentric spatial memory evaluation was especially useful to distinguish between MCI and healthy older adults. Active exploration led to an improved the recall rates of central and allocentric spatial information, as well as to a better fixation in all groups. This led to amnesic MCI patients to obtain better scores in immediate temporal memory tasks. Finally, memory complaints correlated better with the VR test than with classical memory tests. Taken together, these results remark the specific cognitive differences found between these 3 populations that may provide an additional insight with regards to early diagnosis and rehabilitation in pathological performance. More specifically, neuropsychological studies would benefit from VR tests and a multitask and multi-component approach in episodic memory evaluation, and would enhance active information coding in patients suffering from mild to moderate age associated memory impairment.

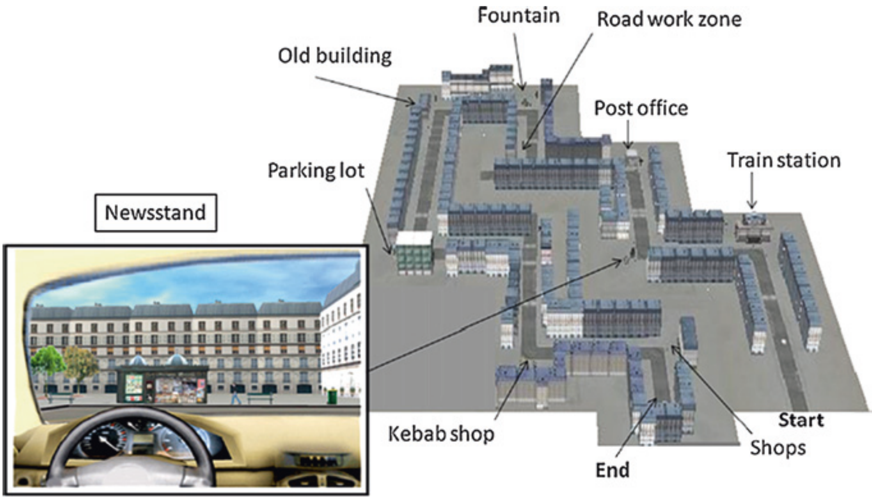

Fig. 13.5 Virtual car used in the study of [39] (used with permission)

13.5.1 Executive Functions

Executive functions are the cognitive abilities that allow individuals to control and regulate their behaviours, making us able to face novel situations and adapt to changes in a flexible manner [53]. In general, terms like executive functioning or control refer to essential mental abilities to deploy an efficient, creative and socially accepted behaviour. In addition, executive functions include a series of cognitive processes, such as anticipation, goal selection, planning, behaviour selection, self-regulation, self-control and feedback. Goldberg [21] uses the metaphor of "orchestra conductor" to describe the role that frontal lobes perform in executive control. According to this metaphor, frontal lobes, main anatomical substrate of executive functions, would have a major role in coordinating the information proceeding from the rest of cerebral structures with the goal to perform propositional behaviours (i.e. goal-directed behaviours).

Tests designed to evaluate executive function are very complex, and one of the main problems may be isolating some functions from others. VR application for the evaluation of executive functions starts in 1998, when Pugnetti et al. [40] designed a virtual building from which the individual had to exit going through different doors. This experimental design resembles a neuropsychological test designed to measure mental flexibility and executive functions, called Wisconsin Card Sorting Test (WCST). The virtual scenario required that participants used environmental cues to support the correct selection of proper doors which are necessary to pass from one room to another. Entry options vary according to shape, colour and number of portholes (windows, peepholes). As it happened in WCST, correct selection criteria were changed after a fixed number of successful trials and it was necessary that the person changed their cognitive strategy from one room to the next one. In their study, though psychometric properties were similar to those of WCST, correlations between different cognitive strategies displayed by patients were quite weak.

A very similar experiment was designed by Elkind et al. [19], who designed the Look For a Match Test (LFAM), a virtual beach, in which the WCST was drawn in some umbrellas, and compared it with computerized WCST. Though the results of the test proposed by Elkind et al. correlated with the Computerized version of WCST, the goal of increasing ecological validity is highly questionable: first, WCST lacks ecological validity, and second, replicating it over a set of umbrellas does not provide anything to the computerized version. In addition, the 3D environment is even more difficult that the classical test, according to self-reports.

Another example is found in the work of Ku et al. [26], who used a virtual environment similar to an Egyptian pyramid to evaluate executive function. The pyramid had hexagonal rooms, each with three doors with different associated shapes, colours and sounds which were reproduced when approaching the door. The user, as it happened in Pugnetti et al. [40], had to choose a door in each room, and the criteria to choose the correct answer changed every certain times. If the user chose the wrong door, a failure sound was reproduced, but the door was open in any case. Rooms were connected among them with corridors in which mummies, obstacles and distractors could be found. The goal was to escape from the pyramid, using similar strategies as in WCST test.

There have been other experiences like the V-STORE, VAPS and V-MALL, even a VR version of the MET (Multiple Errand Test), called V-MET, and developed by Rand et al. [41]. The original Multiple Errand Test was performed in a real supermarket with the evaluator taking the patient into a real setting (with the associated difficulties). V-MET shows a virtual supermarket, and apart from having an evaluation version, it is an intervention tool for people who had a stroke and suffer from deficits in executive function. It examines the ability for multi-task activities and enhances planning and problem solving while the task of shopping is performed. Tasks include selection of a specific recipe, compilation of the list to perform necessary purchases, and purchasing the items appearing on a list. Different features were included to increase the feeling of being within a supermarket: music, sales advertisements and special offers. Products are selected and placed in the trolley using movements of upper limbs and thus patients exercise their motor, cognitive and metacognitive abilities. Users see themselves in V-MET and navigation is performed touching arrows, which move on the screen to the left and to the right. Navigation and interaction with the environment is performed with an haptic device (red gloves including speed and movement sensors), which works with the system GX (a system that uses a chroma key screen to detect the image, capture the silhouette and display it in the program).

All executive function tests presented in this section share the same problems: most of these VR environments are on a experimental phase or under research; they have been studied with small samples; they lack normative data; there is no standardization of the application (in some cases, they are used both for evaluation

Fig. 13.6 Ice cream seller test (by Nesplora)

and rehabilitation, so they are personalized for each patient), and many are not tests, but training and rehabilitation tools.

In order to overcome these problems, Nesplora is developing the Ice Cream Seller test, a multi-task ecological assessment tool based in a VR environment (i.e. an ice-cream shop) to evaluate executive functions in both general and clinical populations. The patient has to perform the role of an ice-cream seller in his first day of work. At the beginning of the test, he will receive instructions that will promote both the correct use of the system plus the proper learning about their duties (training task) followed by the definite task (test). The goals of the training task are to familiarize the user with the test mechanisms, the virtual environment and the hardware, and to avoid computer experience related biases, as all the users will experience the same training task in the same parameters.

The patient will be wearing some VR glasses with a head motion tracker that will allow the user to look around the scenery by turning his head. On the other hand, a virtual arm will allow the user to interact with the objects located in the 3D environment in a similar way as it would be done in the real world. This increases not only the test's ecology but also immersion and sense of presence in the virtual environment (Fig. 13.6).

In the definite task (test), customers will enter the ice cream shop 14 times in groups of 4 people and the user will serve them the specific ice-cream they request following a concrete set of rules predefined by the ice-cream shop boss. The 14 series are divided in two stages: (1) planning stage or *turn giving*, in which the user establishes the order by which he has to serve customers according to previously received rules; and (2) performance stage or *attending customers*, in which customers, one by one, will be required to ask for their desired ice-cream, and will be attended depending on the order set by the user in the planning stage. The user elaborates the ice-cream and gives it to the corresponding customer. If the user changes the order he defined in the planning stage or if he gives the client the wrong ice-cream, he will receive feedback about this event. The total running time of the test will be 1 hour at the most to prevent fatigue associated to the use of VR glasses.

Transversely, the task will suffer some interruptions: distractors (to which the user must avoid paying attention), and set change (ice-cream ingredient configuration change in the 8th series). Variables measured by the Ice Cream Seller test will include: planning (total times the instructions were consulted, correctly set elements, rule learning, planning errors…), learning and working memory (task learning time, errors, consecutive correct answers, number of times the recipe book is consulted, performance improvement curve…), time (time to perform stages 1 and 2, total time), attention (answer to distractors, impulsivity, perseverations, motor activity), cognitive flexibility (perseverations, inhibition, new ice-cream configuration learning time, errors, consecutive correct answers…).

13.6 Conclusions

Since Virtual Reality is used in neuroscience, various works and experimental approaches have been published. Results are promising for the evaluation and treatment procedures to be performed in neuroscience. This technology is more sensitive and objective when it comes to register behavioural changes than classical evaluation methods [47]. In most of the revised research, however, the tendency is to search for correlations with classical evaluation methods, thus leading to mere replications into a digital environment of classical paper-and-pencil tests [19, 26, 40]. The problem with this approach is that it does not improve evaluation methods nor increases ecological validity.

Despite the growing interest that researchers are showing for VR applied to neuroscience, the increasing number of publications and the positive results suggested by this works, the introduction of Virtual Reality in clinical environments is progressing very slowly. One of the main reasons probably lies on the costs associated to VR, which are in any case reducing drastically. Another possible explanation is the lack of mutual understanding between technological and clinical teams; in many of the revised research, the usual procedure is that groups of technologists contact health clinics to obtain samples for validation, thus reducing the study to a mere tool validation, instead of developing a multidisciplinary work and design to collaboratively obtain a clinical application tool. Many designs imply various studies and the crucial decision of copying a widely used test or daring to develop a brand new scenario. One relevant issue is to prevent both with a training part or deep interface studies to prevent that technology becomes a differentiating element between patients and controls, and thus prevent the interference of eventual attitudes of rejection or insecurity against the use of computers, an issue that does not take place in paper and pencil tests.

One of the main problems is the low level of evidence of revised studies. Crosbie et al. [13] made a systematic review in main scientific databases with the terms "virtual reality, rehabilitation, stroke, physiotherapy/physical therapy and hemiplegia". Articles had also to fulfil other requirements such as being published in English on a peer-reviewed journal, or to have used VR in stroke rehabilitation. From the 11 studies found between 1980 and 2005, 3 were classified as level 1 of evidence (imperative and extremely recommendable), 2 were given level 3 of evidence (positive, but not imperative), 3 were given level 4 (positive recommendation, but not conclusive) and the other 3 were given level 5 (neither recommended nor discarded).

In sum, despite the positive results found in research, the evidence level of these studies is still weak and each task needs to be revised deeply before "jumping" into clinical practice. Hence, evidence-based practice studies and further research with larger samples and goals of standardization of VR based neuropsychological assessment procedures are essential ingredients for the future development of neuroscience. Uniform, standard criteria will provide both the clinicians and the patients the warranty of being evaluated or treated with the best available techniques.

At this point, there is a need to mention the potential benefits that further development of this evaluation tools would have in reducing health-care costs when it comes to early detection of many neurodegenerative diseases, such as dementia. Early detection would mean clearer indications for diagnosis and subsequent treatment plan, delayed institutionalization and subsequently, reduce of social and health costs. Some of the first estimations (taken from [59]) point to world wide cost of dementia being up to 156 billion dollars per year. However, many economic studies about health have only included costs related to public administration paying for a treatment and savings obtained for delaying institutionalization. As Wang et al. [55] state, the costs of dementia caregiving (specially, informal caregiving provided by a majority of women—mothers and daughters—who leave their jobs and provide care with no registered cost for public administration, but which mean a significant workforce) increase proportionally with the severity of the dementia process. Hence, studies need to run in parallel, in order to have progressively more precise evaluation and diagnostic tools which take advantages of the latest technologies, and more cost-effectiveness studies that provide evidence on how much money the healthcare services and clinicians would save if these tools were applied for early detection, diagnosis and treatment planning of different neurological conditions.

Finally, while current virtual environments mainly make use of visual and auditory stimuli, it is expected that reduction of costs of underlying technology and further research will facilitate integration of haptic systems, and that haptic feedback will allow users to experience tactile stimuli, making systems more immersive and close to the real world. Haptic gloves such as Rutgers Master II, provide the chance to manage and manipulate virtual objects, as well as train abilities or strength in upper limbs, and olfactory tools are starting to be developed, as well as vibrating platforms for the stimulation of human body's vestibular system. This high correlation with the real world makes that abilities and skills learned within the virtual environment are easy to be transferred to daily life. Future will tell researchers, clinicians, health care providers and stakeholders agree in the high added value that VR based neuropsychological tools may provide in current and future assessment and treatment procedures.

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62. ict.usc.edu/—University of Southern California—Institute for Creative Technologies (USA)
63. www.virtualgamelab.com/—Subdivision of Institute for Creative Technologies
64. www.usc.edu/schools/medicine/departments/cell_neurobiology/research/isnsr/rizzo_docs/13_Neuropsych_Rehab.pdf—Key paper on VR based neuropsychological applications
65. ict.usc.edu/prototypes/vrcpat/—virtual reality cognitive performance assessment test (VRCPAT)
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67. www.neurovr.org/neurovr2/—platform to create your own virtual environments, including assessment tools
68. www.giusepperiva.com/—Webpage of the president of the international association of cyberpsychology, training, and rehabilitation and member of the steering committee of the society for computers in psychology. Many articles and resources available
69. http://www.cybertherapy.info/—This site contains information about the use of advanced technologies—virtual reality, mixed reality, interreality, ambient intelligence—in health care
70. http://www.arctt.info/—Annual review of cybertherapy and telemedicine, updated continously
71. http://profs.formazione.univr.it/npsy-labvr/—Webpage of the Laboratory of Neuropsychology in Verona (Italy), very active in this area of knowledge
72. http://www.pages.drexel.edu/~sg94g745/index.html—Applied Neurotechnologies Lab webpage

Chapter 14
The Role of Virtual Reality in Neuropsychology: The Virtual Multiple Errands Test for the Assessment of Executive Functions in Parkinson's Disease

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Abstract In recent years, Virtual Reality technologies have emerged as assessment and treatment tools in neuropsychology. In this chapter, we will explore the possibility of using Virtual Reality to improve the traditional neuropsychological assessment of executive functions. First, we will discuss the advantages offered by Virtual Reality to more traditional approaches. Then, the chapter details the characteristics of the Virtual Multiple Errands Test (VMET), a virtual reality tool developed using NeuroVR (http://www.neurovr.org)—a free virtual reality platform useful for the assessment and neurorehabilitation. Specifically, the VMET is an assessment protocol of executive functions, where participants are invited to navigate a virtual supermarket, completing tasks that require certain rules. In the chapter, we will present the detailed description of its clinical rationale and its different phases. Furthermore, a systematic analysis of the results obtained in different studies using the VMET will be outlined. Finally, we will discuss the potentiality of the VMET for integrating the traditional neuropsychological evaluation of patients with Parkinson's disease. Detection of early executive deficits in Parkinson's disease could facilitate the identification of patients at risk to develop dementia, and could give the chance to develop early neurorehabilitation interventions.

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List of Abbreviations

VR	Virtual reality
VE	Virtual environment
MET	Multiple errands test
VMET	Virtual multiple errands test
3D	Three-dimensional
PD	Parkinson's disease
OCD	Obsessive-compulsive disorder

14.1 Introduction

The assessment and rehabilitation of impairments of cognitive functions (language, spatial perception, attention, and memory) following neurological damage of different etiology (for example, stroke, traumatic brain injury, and neurodegenerative disorders) have been the focus of considerable research interest. Neuropsychology has developed several measures to effectively evaluate both cognitive and motor abilities. Traditional neuropsychological measures are reliable and have adequate construct validity.

Today, however, a critical challenge for neuropsychology has been to find new way to better measure, understand, and predict daily life abilities. Indeed, one of the most consistent issues with respect to neuropsychological assessment and rehabilitation techniques is the lack of the ecological validity of the traditional protocols, that results in limitations to generalization of new abilities in daily life situations.

The cognitive domain that is most affected by this problem is that of executive functions. It is more and more important to create new tools that better reflect the activities of everyday life to improve the traditional assessment and rehabilitation of executive functions.

Virtual Reality (VR) may be very useful in the assessment and rehabilitation of executive functions since it may increase the ecological validity of current protocols. In fact, VR is used in neuropsychology as "an advanced form of human–computer interface that allows the user to interact with and become immersed in a computer-generated environment in a naturalistic fashion" [60].

An interesting test for executive functions is the Multiple Errand Test (MET), that it has been developed to allow an analysis of the patient in an real-life context [5, 63]. This test requires that the patient completes certain tasks in a real shopping center, following few rules given by the examiner in a span of time.

Unfortunately, it is very difficult to apply the MET in clinical practice, since it requires good motor skills and high economic costs. To overcome these problems and to maintain high ecological validity, we have adapted the software NeuroVR (http://www.neurovr.org) to create a virtual version of the MET (VMET). The VMET is a instrument to assess executive functions, where participants are asked to navigate in a virtual supermarket, comprising of tasks requiring certain rules. This assessment protocol will be presented with a detailed description of its clinical rationale and its different phases. Furthermore, an analysis of the results obtained in different studies using the VMET will be fully discussed.

On the basis of these clinical advantages, we propose that the VMET may be an useful tool to evaluate early executive deficits in Parkinson's disease (PD). Cognitive disorders in PD are not as evident as cognitive impairment in other neurological disorders, and their diagnosis tends to be delayed. Detection of early executive deficits in PD could facilitate the identification of patients at risk to develop dementia, and could give the chance to develop early neurorehabilitation interventions.

14.2 The Role of Virtual Reality in Neuropsychology: Opportunities and Challenges

In recent years the field of VR has grown immensely. Practical applications for the use of this advanced technology encompass many fields, from the training of personnel supported by interactive virtual worlds in industrial centers, to the use of virtual environments for marketing purposes.

One of the newest field that benefits from the advances in VR technology is that of neuropsychological assessment and rehabilitation [8, 47, 51, 57, 60].

From a technological viewpoint, VR consists of a three-dimensional (3D) graphical environment where a user can interact with the environment through a variety of computer peripheral devices. Using visual, aural or haptic devices, the user can experience the environment as if it were a part of the real world.

In neuropsychology, VR is used to offer a new human–computer interaction paradigm in which patients are no longer simply external observers of images on a computer screen but are active participants within realistic virtual worlds [53].

VR appears to be a suitable medium that offers several requirements for effective neuropsychological assessment and neurorehabilitation interventions: repetitive practice, feedback about performance, multimodal stimulation, controlled and secure environments [8, 53, 60]. Specifically, it is possible to control and manipulate tailored exercises within meaningful, ecologically valid and motivating Virtual Environments (VEs) [50]. Indeed, VR simulations can be highly engaging by supporting a process known as *transformation of flow*, defined as a person's ability to exploit an optimal (flow) experience to identify and use new and unexpected psychological resources as sources of involvement [49]. From a psychological perspective, motivation is particularly important for patients consistently engaged in demanding and practice-heavy cognitive exercises.

Besides the opportunity for the experiential and active learning, which motivates the participant, VEs permit to objectively measure behavior in challenging but safe and ecologically valid environments, while maintaining strict experimental control over stimulus delivery and measurement [11, 47, 57].

However, in a recent review, Riva [48] has identified four major issues that may limit the use of the VR system in the assessment and rehabilitation of cognitive impairments:

- The limited possibility of tailoring virtual environments to the specific requirements of the clinical or experimental setting.
- The low availability of standardized protocols that can be shared by the community of clinicians and researchers.
- The high costs (up to $200,000) required for designing and testing a clinical VR application.
- The expensive technical support often required for maintaining a VR system.

The most relevant of these issues is the high costs necessary for design, developing and maintaining a VR application. On one side, it is possible to adapt existing virtual environments or game levels to the specific research or clinical needs. For example, Riva et al. [54] investigated the possible use of the virtual simulation technology offered by Second Life (http://www.secondlife.com) to administer a stress management experiential training, in order to reduce the development and maintenance costs. On the other hand, it is possible to use some existing video game engines (for example, Unity 3D). However, these software require a good programming skills to be used: they are not specifically designed for the creation and customization of highly flexible virtual environments for clinical psychology and behavioral neurosciences.

To address these challenges, Riva and his team developed *NeuroVR* (http://www.neurovr.org) in 2007—a free virtual reality platform based on open-source elements, and the updated version in 2011: *NeuroVR 2* [52].

14.2.1 A New Platform for Neuropsychological Assessment and Rehabilitation: NeuroVR

NeuroVR is a software which allows non-expert users to adapt the content of several pre-designed virtual environments to the specific needs of the clinical setting. The key characteristics that make NeuroVR suitable as cognitive assessment and rehabilitation tool are the high level of control over interaction and the enriched experience provided to the patient.

NeuroVR is composed of several virtual environments, that can be used by the neuropsychologist within a session with the patient. The environments present daily life situations (e.g., Home, Supermarket, Pub, Restaurant, Swimming Pool, Beach, Gymnasium).

Using the NeuroVR Editor (see Fig. 14.1), the specific stimulus can be chosen from a rich database of 2D and 3D objects, and easily placed into the pre-designed virtual scenario by using an icon-based interface (no programming skills are required).

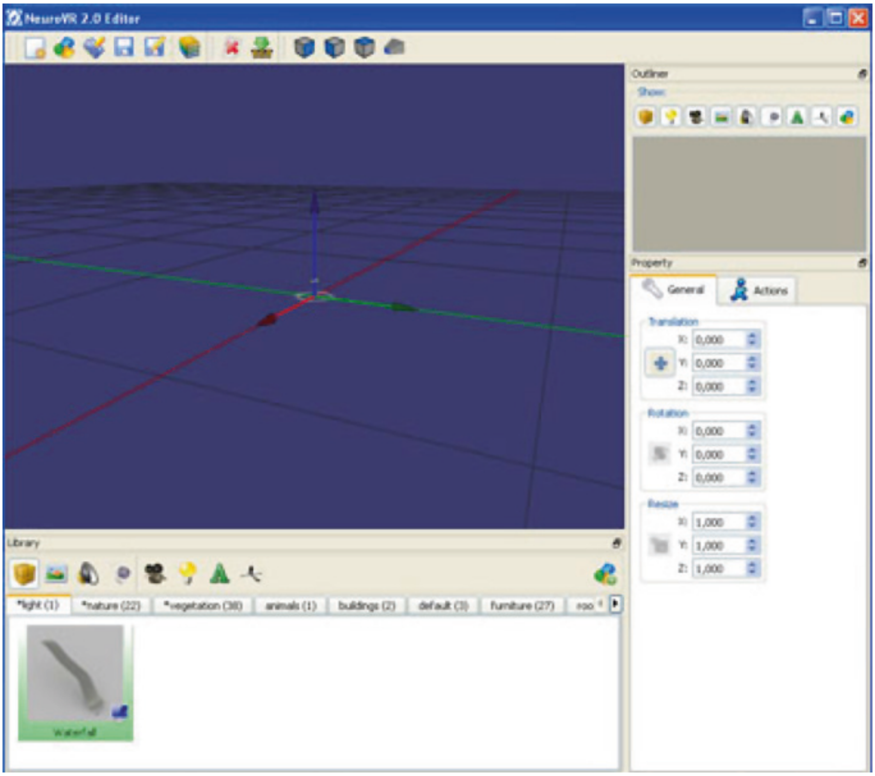

Fig. 14.1 The NeuroVR editor

In addition to static objects, the NeuroVR Editor allows both to add an audio object and to overlay on the 3D scene a video composited with a transparent alpha channel. The editing of the scene is performed in real-time, and effects of changes can be checked from different views (frontal, lateral and top). The edited scene is then visualized and experienced using the NeuroVR Player (see Fig. 14.2).

Through the VR experience, patients practice several different exercises. By directly practicing these cognitive exercises within the VR environment, the patient is helped in developing specific cognitive strategies within a realistic and safe environment.

The use of NeuroVR in cognitive rehabilitation provides the opportunity to create tailored interventions in which the duration, intensity and feedback can be manipulated according to the specific patients' needs. NeuroVR platform allows infinite repetitions of the same assessment or training task: thanks to its flexibility, it is possible to easily modify the stimulus presentations, the task complexity, the response requirements, and the type of feedback according to patients' cognitive disabilities.

An example of the potentiality of NeuroVR as effective tool for a new class of neuropsychological applications for improving the traditional neuropsychological

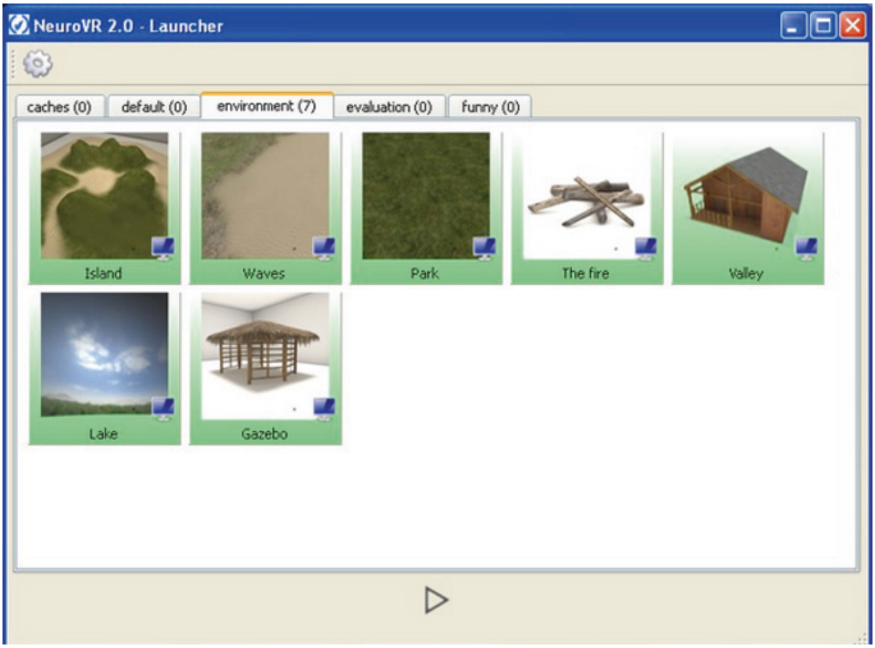

Fig. 14.2 The NeuroVR player

evaluation of cognitive functions is the virtual version of the Multiple Errands Test (VMET).

The different techniques used in the VR sessions for the assessment of executive functions in the VMET are detailed in the following paragraphs.

14.3 From Multiple Errands Test to Virtual Multiple Errands Test

In the recent decades, neuropsychology, cognitive psychology and cognitive neuroscience have worked together to understand the complexity of cognitive processes, the functional neuroanatomy underpinning those cognitive domains, and the implications of cognitive impairments in neurological patients for models of normal cognitive functioning.

One of the most complex ability of the human mind is its ability in continuously orienting cognitive resources to effectively respond both to environmental and internal demands. Traditionally, these high-level cognitive abilities have been called *executive functions*, and they have been the focus of considerable research interest.

As suggested by Chan et al. [17], the term “executive functions” is an umbrella term including a wide range of cognitive processes and behavioral competencies.

They include problem-solving, planning, sequencing, the ability to sustain attention, resistance to interference, utilization of feedback, multitasking, cognitive flexibility, and the ability to deal with novelty [15, 26, 62, 64, 65].

Impairments of executive functions are extremely common in neurological patients, specifically in those presenting frontal cortex injury (for example, see [7, 13, 14, 55].

As summarized by Chan et al. [17], an increasing number of neuropsychological tests have been developed to assess the presence of executive deficits in different clinical population. The assessment of executive functions has been generally performed in clinical settings, usually via paper-and pencil questionnaires or laboratory tasks: for example, it may include the Cambridge Neurological Inventory [19], the Design Fluency Test [31], and different types of Tower tests [28, 61].

However, there are some critical issues in the traditional neuropsychological evaluation of executive functions [17]: a more ecological and prompt neuropsychological evaluation of executive functions is essential to measure the specific cognitive profile of different individuals [18, 25].

Furthermore, even if many patients with frontal lobe lesions have shown scores on traditional neuropsychological tests similar to controls, they are characterized by several difficulties in daily life activities [63]. Indeed, the traditional assessment does not reflect the complexity of executive functions in ecological contexts: a more detailed assessment may evaluate if individuals are able to formulate, store and check all the goals and sub-goals in order to effectively respond to environmental and/or internal demands.

These aspects led clinicians and researchers to develop a more ecological evaluation of executive functions. In this direction, there are some instruments developed to measure executive deficits in situations similar to daily ones, such as the Behavioral Assessment of Dysexecutive Syndrome [70] and the Multiple Errands Test (MET) [5, 63].

More specifically, the MET is a functional test for evaluating executive functions in daily life originally developed by Shallice and Burgess for high functioning patients [63]. Specifically, it was also adapted into the simple [5] and into the hospital version [33]. Contrary to the Behavioral Assessment of Dysexecutive Syndrome or other laboratory-based tasks, MET is performed at a real shopping mall or in a hospital environment, and it requires the completion of various tasks without breaking a series of arbitrary rules.

In the simplified version, the test is composed of three main tasks. The first involved purchasing six items (e.g., small brown loaf). The second task involved locating and recording four items of information (e.g., the closing time of the library on Saturday). The third was meeting the clinician at a designated point (under the clock) and stating the time 20 min after beginning the test. While performing the exercise, participant has to follow some rules, such as for instance: "Do not speak to the person observing you unless this is part of the exercise."

The clinician follows the participant, recording different kinds of errors, from a task failure (e.g., failed to purchase keying) to a rule breaking (e.g., shouted question to shop staff).

As explained, the procedure is, as many situations outside of the laboratory, “open” or “ill-structured” [24]: there are many possible courses of actions. In this way, the executive functions stimulated are several since participants have to decide how to plan the actions, how to list the steps necessary to achieve the main task, how to formulate, store and check all the goals and sub-goals, and how to compare the outcome of action with the desired goal.

Being a “real-life” test requiring the performance in very common daily activities, the MET has good ecological validity [12]. However, to adequately perform the Multiple Errands Test, the patient should go with the clinician to a real mall, and this necessarily requires good motor skills; besides the “real world” is not a controlled and secure environment, and it is not possible to maintain a strict experimental control over stimulus delivery and measurement. Furthermore, this procedure can be particularly demanding both for a patient whose cognitive system is failing and for a therapist, since it is time consuming and requires high economic costs.

To address these issues, a virtual version of the Multiple Errands Test has been developed and tested.

14.3.1 The Virtual Multiple Errands Test

Rand et al. [45] developed a first version of the Virtual Multiple Errands Test as an assessment tool for executive functions, within the virtual mall [43], a functional virtual environment consisting of a large supermarket which was programmed via GestureTek’s IREX video capture virtual reality system.

The VMall has been developed to provide an engaging task which can offer post-stroke participants an opportunity to practice different shopping tasks without leaving the treatment room [44].

On these premises, Riva and his team exploited the potentiality of NeuroVR previously described to develop and test an advanced assessment tool of executive functions, namely the VMET.

From a technical point of view, the VMET (see Fig. 14.3) consists of a Blender-based application that enables active exploration of a virtual supermarket where participants are requested to select and buy various products presented on shelves. The user enters the virtual supermarket and he/she is presented with virtual objects of the various items to be purchased.

Moreover, using a joypad, the participant is able to freely navigate in the various aisles (using the up-down joypad arrows), and to collect products (by pressing a button placed on the right side of the joypad), after having selected them with the viewfinder.

The virtual supermarket contains products grouped into the main grocery categories including beverages, fruits and vegetables, breakfast foods, hygiene products, frozen foods, garden products, and pet products. Signs at the top of each section indicate the product categories as an aid for navigation.

Fig. 14.3 The VMET

The procedure has been adapted by Shallice and Burgess [5, 63]. After an initial training phase with an another virtual supermarket, the examiner shows the virtual supermarket shop and illustrates the different sections.

Participants are given a shopping list, a supermarket's map, some information about the supermarket (opening and closing time, products on sale, etc.), a pen, and a wrist watch.

The instructions are illustrated to the participants and the rules are explained with reference to the instruction sheet. The VMET is composed of four main tasks. The first involved purchasing six items (e.g., one product on sale). The second involved asking examiner information about one item to be purchased. The third involved writing the shopping list 5 min after beginning the test. The third involved responding of some questions at the end of virtual session by using useful material (e.g., the closing time of the virtual supermarket).

This is the list of rules:

- you have to execute all the proposed tasks, but you can run them in any order;
- you cannot go in a place unless this is a part of a task;
- you cannot pass through the same passage more than once;

- you cannot buy more than two items per categories (look at the chart);
- take as few time as possible to complete this exercise however without hurry;
- do not talk to the researcher unless this is a part of the task;
- go to your "shopping cart" after 5 min from the beginning of the task and make a list of all the products that you bought.

The examiner started the task without talking with participant not even to answer to the questions. The time stopped when the participant said "I finished". During the task, the examiner took notes about participant's behaviors in the virtual environment. As suggested by Shallice and Burgess [63], the errors were categorized as following:

- task failure, namely a task not completed satisfactorily;
- inefficiencies and strategies, where a more effective strategy could have been applied to accomplish the task;
- rule breaks, where a specific rule listed in the instructions has been violated;
- interpretation failures, where the requirements of a particular task are not misunderstood.

An analysis of the results obtained in different studies using the VMET will be deeply described in the following paragraph.

14.3.2 The Potentiality of the VMET for Neuropsychology

The VMET has good psychometric properties. In a first experiment, two independent researchers scored 11 videos, each one showing a subject completing the VMET. In a second experiment 7 researchers scored two videos, each one showing a participant performing the VMET. Results showed a good reliability of the VMET [20, 21].

Furthermore, the VMET has been validated with different clinical population. Raspelli et al. [46] demonstrated the ecological validity and initial construct validity of the VMET. The study population included three groups: 9 post-stroke participants, 10 healthy young participants, and 10 healthy older participants. Correlations between VMET variables and some traditional executive functions measures provide preliminary support for the ecological and construct validity of the VMET. Furthermore, performance obtained at the VMET provided a distinction between the clinical and healthy population, and between the two age control groups.

La Paglia et al. [35] used the VMET to evaluate the executive functions in daily life in 10 patients suffering from obsessive-compulsive disorder (OCD) and 10 controls. The execution time for the whole virtual task was higher in patients with OCD compared to controls, suggesting that patients with OCD need more time in planning than controls. Furthermore, patients showed more difficulties in following the rules and sustaining attention than controls. These results provided initial support for the feasibility of the VMET as assessment tool of executive functions in OCD patients. Specifically, the significant correlation found between the VMET and the neuropsychological battery supports the ecological validity of VMET as an instrument for the evaluation of executive functions in patients with OCD.

Cipresso et al. [20, 21] used the VMET to investigate deficits of volition in OCD patients. The study involved thirty participants (15 OCD patients and 15 controls) during task execution and the relative interferences.

Results showed specific deficits in OCD patients, as defined in the following classification:

1. break in time: to go to the shopping chart after 5 min;
2. break in choice: to buy two products instead of just one;
3. break in social rules: to go into a specific place and to ask the examiner what to buy.

Albani et al. [4] used the VMET to investigate decision-making ability in 12 patients with Parkinson's disease as compared to 14 controls. In the early-middle stages of Parkinson's disease, polysomnographic studies show early alterations of the structure of the sleep, which may explain frequent symptoms reported by patients, such as daytime drowsiness, loss of attention and concentration, feeling of tiredness. Five of 12 patients with Parkinson's disease showed abnormalities in the polysomnographic recordings associated to significant differences in the VMET performance.

However, as underlined by Chan et al. [17], this advanced technology should be carefully used in clinical setting, in particular with regard to those patients who are not familiar with computerized test.

To address this issue, Pedroli et al. [42] tested the usability of the VMET with 21 healthy participants and 3 patients with Parkinson's disease. To evaluate usability, they used the System Usability Scale (SUS), a "quick and easy to use" measure developed by Brooke [10]. Brooke defines usability as "the subjective perception of interaction with a system." Healthy participants gave a good usability for the VMET. As regards patients, results showed that a good training phase before the test is crucial to apply the virtual protocol.

These encouraging results led us to consider the VMET as an useful tool to evaluate executive deficits in Parkinson's disease.

14.4 The Potentiality of the VR in the Assessment of Executive Functions in Parkinson's Disease: A Possible Approach

Contrary to what firstly described James Parkinson [41], the evidence is that the cognitive impairment is extremely common in Parkinson's disease (PD) and affects a variety of cognitive domains, including memory, language, executive functions, visuo-spatial abilities. Besides characteristic motor signs, a number of different cognitive deficit has been received a relevant clinical attention in PD [23, 32, 36, 40, 68, 69]. Similar to motor symptoms, the characteristics of cognitive impairments in PD can be extremely variable, both in terms of what cognitive functions are impaired and the timing of onset and rate of progression (for example, see [67].

As cognitive deficit is a common complication of PD, and since it is associated with significant disability for patients and burden for caregivers, it is crucial to fully evaluate the neuropsychological profile in this population.

There are convincing evidence demonstrating the clinical importance of cognitive impairment for the quality of life of patients and their caregivers, as well as the health-economic impact [2, 3, 59]. Impairment of executive functions constitutes the core feature of neuropsychological profile dysfunction in PD [16, 39]. In PD, indeed, executive dysfunctions are similar, but not identical to those seen in frontal lobe patients, and are conceived to represent a dysfunction of the fronto-striatal neural circuitry [56, 58]. Because of the impact on the patient's quality of life, early detection and rehabilitation of executive dysfunctions is crucial in the management of PD. So, it is fundamental that we improve our understanding of this common and disabling complication in PD, both in terms of neuropsychological assessment and rehabilitation strategies.

Based on these premises, we argue that the VMET could be an useful tool for evaluating executive deficits in PD.

14.4.1 The Virtual Multiple Errands Test for the Assessment of Executive Functions in Parkinson's Disease

As the PD progresses, a relevant proportion of patients will develop dementia [1, 9, 22, 27]. The focus is now to identify patients with a potentially higher risk of dementia with the possibility to implement an early and individualized cognitive rehabilitation treatment to improve their quality of life.

As previously underlined, executive deficits constitute the core clinical marker of neuropsychological profile of PD patients.

Particularly, an increasing number of longitudinal studies suggests that early executive dysfunction is predictive of the conversion to dementia [6, 29]. In this perspective, it has been recently proposed to use the term "mild cognitive impairment in PD" [37, 38]. Although the term "mild cognitive impairment" applied to PD is controversial [66], it is more frequently used and more widely accepted than alternative terms.

Mild cognitive impairment in PD may be an useful clinically concept to define a cognitive decline that is not normal for age, but it is essentially associated with normal functional activities. Several studies demonstrated that mild cognitive impairment predicts the development of dementia, which can occur in up to 80 % of PD patients over the long term [6, 30].

Detection of early executive deficits in PD could facilitate the identification of patients at risk to develop dementia, and may give the chance to develop early neurorehabilitation interventions.

In such context, we argue that the VMET may significantly improve the traditional assessment of executive functions in patients suffering from mild cognitive impairment due to PD.

Thanks to the VMET, it will be possible to evaluate:

- the real functional status of mild cognitive impairment due to PD, as manifested in terms of executive dysfunctions, that had not been fully acknowledged in everyday life scenarios;
- the ability of patients with mild cognitive impairment due to PD in formulating, storing and checking all the goals and sub-goals in order to effectively respond to environmental demands in ecological situations.

14.5 Conclusion

In recent years, VR technologies have emerged as assessment and treatment tools in neuropsychology. Neuropsychology is one of the most promising field, where the advantages of using VR are still to be further explored. This is a domain of great interest, in which the integration of new technologies may improve the ecological validity of the current approaches. Today, in fact, a critical challenge for neuropsychology has been to find new way to better measure, understand, and predict everyday abilities. Indeed, one of the most consistent issues with respect to neuropsychological assessment and rehabilitation techniques has been limits in the ecological validity of the traditional protocols, that results in limitations to generalization of new abilities in daily life situations.

In this chapter, we have explored the possibility of using VR to improve the traditional neuropsychological evaluation of executive functions.

First, as the VR may have an important role in neuropsychology, it is important that it is extensively defined within its specific features. Indeed, in order to ensure an adequate development of virtual assessment tools, we have discussed the opportunities and challenges that Virtual Reality may provide to more traditional approaches. Specifically, to solve some limitations in the use of VR in clinical practice, Riva and his team developed *NeuroVR*, a new open- source platform for neuropsychological assessment and rehabilitation. Then, we detailed the characteristics of the VMET for the assessment of executive deficits, that tries to enhance the traditional approaches used in the neuropsychological evaluation of executive functions by means of VR.

In fact, it is crucial to create new tools that better reflect the activities of everyday life to improve the traditional assessment and rehabilitation of cognitive functions. The cognitive domain that is most affected by this problem is that of executive functions. VR may be very useful in the assessment and rehabilitation of executive functions since it may increase the ecological validity of actual protocols.

The VMET is an assessment protocol of executive functions, where participants are required to navigate in virtual supermarket, comprising of tasks that abide by certain rules. This assessment protocol has been presented with the detailed description of its clinical rationale and its different phases.

Furthermore, a systematic analysis of the results obtained in different studies using the VMET has been fully described.

Finally, we discussed the potentiality of the VMET for integrating the traditional neuropsychological evaluation of patients with PD. As the PD progresses, a relevant proportion of patients will develop dementia [1, 9, 22, 27]. The focus is now to identify patients with a potentially higher risk of dementia with the possibility to implement an early and individualized cognitive rehabilitation treatment to improve their quality of life.

Identification of early executive deficits in PD with the VMET could facilitate the identification of patients at risk to develop dementia, and could give the chance to develop early neurorehabilitation interventions.

Obviously, much more researches are needed to evaluate the potentiality of the VMET, especially in terms of its temporal stability, namely the test–retest reliability, and the criterion validity for PD.

Furthermore, from a psychological perspective, neuropsychological evaluation is particularly onerous for patients: user interfaces may play an important role in making VR applications more user-friendly and motivating.

Until recently, game interfaces were limited to a computer mouse, arrow keys on a keyboard, or a joystick. Recently, there has been a progressive diffusion on home gaming market of advanced game technologies (such as Microsoft Kinect and Nintendo Wii) that allowed the use of a large series of interactive devices at a low cost. For example, the Microsoft Kinect can sense the full-body without the use of markers. The Kinect sensor, originally designed for recreational use, are now being adapted by clinicians and researcher for therapeutic purposes [34].

Most of such devices, beyond a low cost, makes available the Software Development Kit (sdk) for integrating third-part software. For future studies, it is possible to use such commercial devices to integrate new interactive functionalities in the NeuroVR platform, to be used and tested in VMET.

A recently Italian funded project "VRehab. Virtual Reality in the Assessment and TeleRehabilitation of Parkinson's Disease and Post-Stroke Disabilities" will offer the right context to test the potentiality of the VMET as an assessment tool of executive deficits in PD.

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Chapter 15
NeuroVirtual 3D: A Multiplatform 3D Simulation System for Application in Psychology and Neuro-Rehabilitation

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Abstract In the last decade the use of Virtual Reality platforms in psychology and neurorehabilitation increased thanks to a higher availability of low-cost technology and a wider acceptance from the clinical world. Nonetheless multiplatform taking into consideration the combined use of innovative low-cost technologies are still missing. This chapter will extensively discuss the opportunities offered by the NeuroVirtual 3D platform in term of technologies innovations for the clinicians. After an overview of the state of the art in the field, a comprehensive discussion will focus above all on the low-cost stereo cameras and the Eye-Trackers, both more and more used in the assessment and neurorehabilitation of motor and cognitive abilities.

15.1 Introduction

The use of virtual reality (VR) in psychology and neurorehabilitation has continued to increase. However, it seems likely that VR can be much more than just a tool to provide exposure and desensitization.

In this sense virtual reality has great potential for use in the rehabilitation of everyday life activities, involving cognitive and motor functions. The use of simulated environments, perceived by the user as comparable to real world objects and situations, can overcome the limits of the traditional tests employed to assess, by keeping intact its several advantages.

VR systems in stroke neurorehabilitation both cognitive and motor are rapidly expanding and a large number of interesting platforms are currently being developed

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and tested. Morganti et al. [41] and Ma and Bechkoum [38] proposed a combination of standardized paper and pencil neuropsychological tests and a virtual reality-based assessment (VR-Maze test and VR-Road Map) for the evaluation of spatial orientation in brain injured patients. Compared to a control group, 4 male patients with brain damage revealed significantly shorter times and greater errors in solving a virtual spatial task. In a recent review, Tsirli et al. [61] described past and ongoing research of VR applications for unilateral neglect post-stroke evaluation: they suggested that VR could improve existing assessment methods by providing information about head and eye movements, postural deviations, and limb kinematics.

The use of Virtual Reality systems in motor rehabilitation provides the opportunity to create tailored interventions in which the duration, intensity and feedback can be manipulated according to the specific patient's needs. In the last decade, many investigators have developed and tested the effectiveness of VR-based platforms for rehabilitation of the arm [7, 15–17, 34, 55] or hand [6] in stroke patients. Arm motor deficits are, in fact, prevalent post stroke: for example, 55–75 % of stroke patients are affected by upper limb (UL) at 3 and 6 months [43, 31]. Merians et al. [40] verified the effectiveness of VR training of the hemiparetic hand on 8 post-stroke patients using a system that provides repetitive motor re-education and skill reacquisition. Results showed that patients improved in fractioning, range of motion and speed and these changes translated to improvements in the real-world measures. They suggested the use of VR environments in movement re-education since they have the potential to improve existing rehabilitation therapies. A recent meta analysis published on Stroke [57], which included 12 studies (for a total of 195 patients) highlighted that rehabilitation protocols that include VR are the most effective. These studies support the hypothesis that virtual environments are very useful in motor rehabilitation since they increase the efficacy of actual therapies.

15.2 NeuroVirtual 3D Platform: Main Issues and Aims

If, on the one side, the use of VR in rehabilitation represents a consolidated and rising scientific trend, the use of this tool in clinical practice is very limited, especially on a national level. According to recent reports, in Italy and Europe VR is employed especially within clinical research projects while its professional use is extremely limited. This finding cannot be explained by the immaturity of technological components, which have been developed thanks to the huge growth of the videogames market, nor in terms of the lack of scientific evidence about the efficacy of this approach.

A more suitable explanation of the absence of diffusion of VR in the rehabilitative field is related to two specific problems: (a) the lack of easily usable, low cost and high reliability tools; (b) the limited availability of rehabilitative contents, which provide interactive simulations aimed at practice and therapeutic stimuli.

Another problem is represented by the absence of integrated solutions between research and clinic: often therapists are interested not only in taking care of the patient through the use of VR but also in collecting important data for the improvement of the efficacy of the therapeutic solutions.

Finally, the need to assess the so called "transfer of training" (that is to establish to which extent the results obtained through the virtual reality exposure can be transferred to daily life activities) should not be overlooked. In this perspective, an emerging need is to effectively use the possibilities offered by the new mobile technologies (smartphone, wearable sensors) to permit the patient to carry on exercises also at home and to give to the therapist important indications related to the level of compliance with the therapeutic instructions.

Starting from these premises, the NeuroVirtual 3D platform aims at addressing these challenges by designing, developing and testing a low-cost integrated virtual reality solution for applications in clinical psychology and neuromotor rehabilitation.

The platform, which includes the features of the software NeuroVr 2.0 (http://www.neurovr.org/neurovr2/) [51], will be expanded as follows:

- development of a software interface for integrating into NeuroVirtual 3D commercially-available peripherals that support neuromotor rehabilitation (es. dataglove, haptic devices, Kinect);
- integration with eye-tracking devices;
- enable support for multi-users interaction and communication through virtual humans;
- development of 3D contents for mobile devices (android, iPhone/iPad);
- development of a web repository of 3D scenes for allowing researchers and rehabilitation professionals to share their virtual environments and protocols.

The development of the platform will be done on the basis of specific ergonomic and clinical trials based on the proposed platform.

15.3 The Scientific-Technological State of the Art

In the last decade, the use of VR in neurorehabilitation rose in a significant way and an increasing number of experimental findings suggested that this technology can positively impact upon cognitive and motor functional recovery [1–3, 33, 37, 52, 57]. The rationale for the use of VR systems in the rehabilitation field is based on a series of advantages widely documented in the scientific literature:

- Neuroplasticity: VR allows the use of scenarios based on principles that regulate and facilitate neuroplasticity (for example: exercise intensity, exercise frequency, "enriched stimulation", etc.) that provide a neuro-biological basis for the recovery of cognitive and motor functions.
- Personalized training: VR is based on highly automated functioning mechanisms that require a minimal contribution by the rehabilitation professional, who may make use of the possibility to customize the intensity and the difficulty of the training based on the specific necessities of the patient.
- Involving tasks: in the VR, the content of rehabilitative exercises may be planned to the extent of defining some tasks oriented to re-train specific abilities (for example, to reach an object), and in the same time integrating in some

recreational scenarios to maintain a high level of involvement and compliance in the patient in the execution of exercises. In particular, a lot of studies evidenced the role of VR in augmenting the sense of Presence [49, 50] and the optimal experience [25] in the rehabilitative process.

- Tracking and objective/quantitative measure: thanks to the sensors integrated in VR systems (for example: cranial movements tracking sensors, sensors for superior limbs, dataglove etc.) it is possible to record a high quantity of data with regard to actions executed by the patient inside the virtual scenario and to use these data to create some indexes of performance in order to measure in a quantitative and objective way the improvement in performance observable in the course of the rehabilitative process.
- Transferring of the training in ADL: many studies that investigated the use of VR in the neurorehabilitative field evidenced the potential offered by this methodology to transfer the results of the re-learning of cognitive and motor abilities that were damaged in the activity of day living (ADL). The positive impact of VR on ADL is documented by many studies and is explained by the fact that VR offers the possibility of including rehabilitative exercises in real life context simulations (for example: buying an object in a virtual supermarket may help to rehabilitate executive functions in patients with frontal lesions).

These advantages, documented by an extensive literature and clinical case record in different pathological fields (from mental diseases to neuropsychological, from acquired brain injury to neurodegenerative diseases and ictus) increased the interest of sanitarian organizations and rehabilitation professionals in this innovative methodology. This increasing interest is documented by the increase in the number of studies, by the proliferation of conferences and scientific publications, the increase in public and private finance for research into clinical applications of VR. From a commercial point of view there is a limited and varied offering of VR systems for rehabilitation (neurological or psychological). The main goal of the NeuroVirtual 3D platform is to design and develop a low-cost VR platform for applications in the fields of mental wellbeing and neuromotor rehabilitation. The specific technical innovations provided by the platform are described in the following sections.

15.4 Interfaces Development for Input/Output Hardware Devices for Applications in Neurorehabilitation (e.g. Dataglove, Haptic Devices, Kinect)

Recently, there has been a progressive diffusion on the home gaming market of advanced game technologies (such as Microsoft Kinect, Nintendo Wii) that allow the use of a large series of interactive devices at a low cost [26, 27, 35, 47]. Most of these devices, in addiction to their low cost (due to the fact of being targeted at the consumer market), make available Software Development Kits (sdk) to integrate third-part software. The NeuroVirtual 3D platform aims to use such commercial

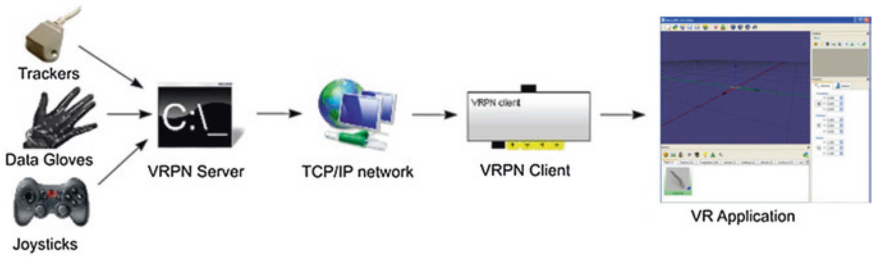

Fig. 15.1 Device- NeuroVirtual 3D interaction interface

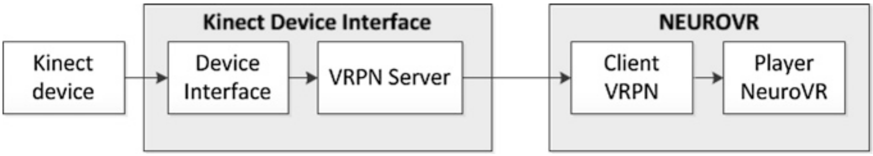

Fig. 15.2 Kinect-NeuroVirtual 3D. Interaction interface

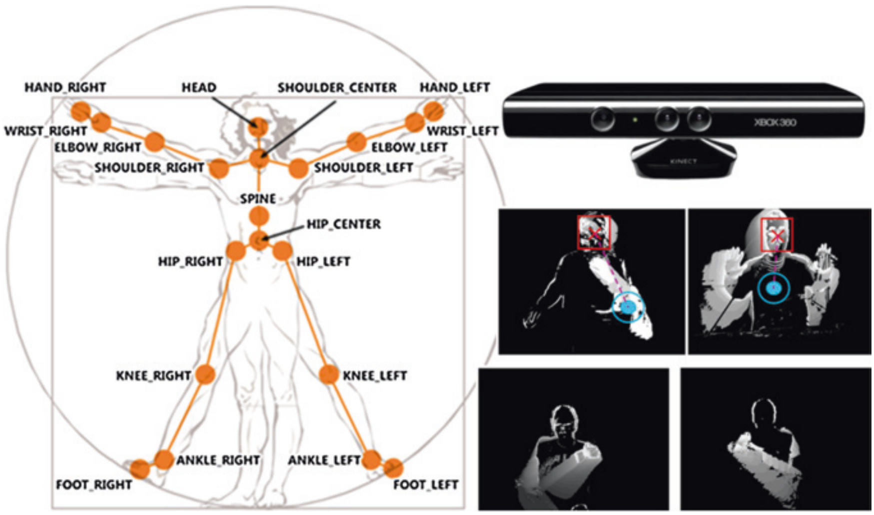

Fig. 15.3 Video signal processing from kinect and Avatar structures

devices to integrate new interactive functionalities in the NeuroVR platform, to be used and tested in a neurorehabilitative framework. This strategy is to obtain a double result: On one hand, to add new interactive features to the VR platform to allow an higher range of content and neurorehabilitative exercises; on the other hand, to take advantage from these technologies to offer solutions based on low cost and high availability (Figs. 15.1, 15.2 and 15.3).

15.4.1 Integration with Eye-Tracking Devices

For many decades the recording and processing of cerebral and oculomotor activity is a relevant methodology for clinical and neuropsychological assessment [19, 30]. In particular, an interesting instrument that has been increasingly used in the past decades for clinical assessment is the Eye-tracker [20, 21, 62]. This advanced device /method is able to track and record, with a high spatial and temporal precision, ocular movements, synchronizing them with the stimuli. Traditionally the standard methodology uses validated paradigms, such as saccadic, anti-saccadic and smooth pursuit [4, 12, 13, 18, 24]. Moreover, recently, the framework of such instruments has been widely extended, moving from the classic clinical assessment to a more active use of such an instrument as input platform. In this sense, the most extensive use is the Alternative and Augmented Communication (AAC), through which it is possible to communicate "by the means of eye movements", also for patients with motor or communication deficit [10, 11]. Through the integration of ocular tracking in the NeuroVirtual 3D platform, it will be possible to obtain an effective methodology to monitor eye-movements during the immersive experience, obtaining useful information on cognitive activity of the participant, such as visual attention, perception, reasoning, information pursuit, and the evaluation of complex environmental stimuli. In particular, the integration of the eye-tracker and of the Brain Computer Interface (BCI) will provide the following advantages:

- Increased accuracy in assessment and diagnostics of ongoing rehabilitation processes;
- Ability to correlate specific mental states with specific activities executed into the virtual environments, through the use of environmental markers that allow the synchronization of the ocular path with the action performed by the user.
- Ability to study the variables related to attention, perception, and cognition in the framework of simulations representing realistic situations and daily contexts, increasing the ecological validity of gathered data.

15.4.2 Development of Multi-User Interaction and Communication Through Avatars

Another innovative technological solution introduced by the NeuroVirtual 3D platform is the development of multi-user functionalities, at the present missing in the NeuroVR platform.

The use of virtual environments in multi-user modality permits an increase the applicability of such a platform in the rehabilitation framework, allowing an extended use of complex paradigms, such as including social situations (e.g., the patient has to learn to manage a social phobia in a virtual environment, such as public speaking) or in rehabilitative situations, where the co-presence of a therapist represents an added value in the patient motivation to perform the exercises (e.g., in telemedicine).

15.4.3 Development of the Ability to Display 3D Content on Mobile Devices

The growing diffusion of mobile platforms, such as smartphones and tablets, represents a meaningful chance in rehabilitation, unfortunately not enough explored yet. Thanks to the progressive raising of computational and memory capabilities, these devices could provide interactive 3D simulation with a high level or realism and complexity, that can effectively be used for rehabilitation, to allow the patient to continue exercises in mobility or at home. The objective is to provide rehabilitative virtual contents and exercises to be used in a hospital environment with the therapist and to be repeated where the patient desires (e.g., at home) through players installed in mobile devices, such as iPhone, iPad and Android.

15.4.4 Development of an Online Repository of 3D Scenes for the Sharing of the Environments Among the Software Users

A further innovation proposed by the NeuroVirtual 3D platform is the creation of an online repository with validated clinical 3D contents, containing also protocols and procedures to share with rehabilitation experts' community, operating with virtual reality or simply interested in experimenting with this approach. The ability to easily access this content will encourage and promote a wider use of the NeuroVirtual 3D platform and will allows users to experiment on a large-scale to obtain a higher number of clinical evidences to reach a critical mass of studies to support the use of VR in research and in the clinical practice.

The evolution of the platform is to allow the translation of the medical therapy principles, through virtual environments, to the psycho-behavioral and motivational training techniques—typically residential—conveying them through new generations distance learning systems, allowing, thanks to the interaction with immersive and interactive 3D environments, a greater emotional involvement, thus overcoming the main limitations of e-learning.

15.5 The Clinical Use of Virtual Reality

The use of virtual reality (VR) in clinical psychology has become more widespread [48]. The key characteristics of virtual environments for most clinical applications are the high level of control of the interaction with the tool, and the enriched experience provided to the patient [58]. Typically, in VR the patient learns to cope with problematic situations related to his/her problem. For this reason, the most common application of VR in this area is the treatment of anxiety disorders, i.e., fear of heights, fear of flying, and fear of public speaking [23, 63]. Indeed, VR exposure therapy (VRE) has been proposed as a new medium for exposure therapy [48] that is safer, less embarrassing, and less costly than reproducing the real world situations. The rationale is simple: in VR the patient is intentionally confronted with the feared stimuli while allowing the anxiety to attenuate. Avoiding a dreaded situation reinforces a phobia, and each successive exposure to it reduces the anxiety through the processes of habituation and extinction.

However, it seems likely that VR can be more than a tool to provide exposure and desensitization [48]. As noted by Glantz et al. [28]: "VR technology may create enough capabilities to profoundly influence the shape of therapy." (p. 92). In particular we suggest that embodiment through VR might have important applications in other fields of rehabilitation, and specifically in the treatment of chronic pain conditions and weight disorders.

Virtual reality (VR) can provide the appropriate experience to support remote rehabilitation [8, 36, 57]. By VR we refer to a set of technologies that attempts to create an immersive computer display that surrounds the participant [22]. VR replaces direct vision and audition of the real environment with synthesized stimuli, and can also integrate haptic (tactile and force) cues representing virtual objects or remote interactions [46, 5]. VR is able to provide real time feedback to the participant [39, 9], comprised of parallel streams of sensory information (visual, sound, or haptics; [1]). The capacity of VR-based systems as a facilitation tool for functional recovery by engaging brain circuits, such as motor areas, has been demonstrated [2].

A recent review study has shown that such systems can be effective and motivating for rehabilitation therapies involving repetition and feedback [33]. It seems that motivation is a key factor for applications based on augmented feedback using VR for rehabilitation of motor skills of patients with neurological disorders [54]. In particular, there is evidence for the effectiveness of such approaches for the rehabilitation of upper limbs in patients with stroke [14, 31, 37, 57].

Apart from immersion and motivation, a critical ability of VR in the context of neurorehabilitation is the possibility to induce ownership of a whole virtual body [60] or specific body parts such as the hand/arm [59] or belly [42].

The fact that a virtual body part can be incorporated into the body schema based on synchronous visuo-tactile correlations has opened new paths for examining the mechanisms of body perception. The strength of the virtual illusion is reinforced when, to the visual co-location, synchronous visuo-motor correlations are provided, e.g., with the person controlling the body movements (arms, legs, etc.) of the avatar, who mimics her movements [29, 56].

In clinical terms, manipulations of a virtual body could have implications not only for motor or sensory rehabilitation but also for psychological treatment in different pathologies involving body perception, such as painful phantom limbs, regional pain syndrome (Llobera et al. in press), eating disorders [45, 53], or burns [32]. Recently, a novel approach following these cognitive principles of body perception has been proposed [44].

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Part IV
Applications in Motor Rehabilitation

Chapter 16
Rehabilitation at Home: A Comprehensive Technological Approach

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Abstract Novel tracking devices, like Nintendo Wii and balance board and Microsoft Kinect, have open the possibility to do rehabilitation at home, where patients are guided by video-games. It was soon recognized however, that to be effective, rehabilitation games cannot work as stand-alone applications but must be embedded into a broader architecture involving patients, therapists, clinicians, hospitals and health providers. This is specifically the approach pursued inside the REWIRE project, recently funded by the EU, that has developed three main hierarchical components: a hospital station (HS), a networking station (NS), and a patient station (PS). The PS, installed at patients' homes, guides the patient through rehabilitation using engaging and video games each developed to train a specific function. A framework for defining an objective progression based on Gentile's taxonomy is introduced. Games have been realized through a Game engine that combines classical functionalities with advanced functionalities specific to rehabilitation: adaptation, monitoring, feed-back and data log. Moreover, the exergames realized share a wider theme that allows increasing patients' motivation. A few of these games will be illustrated. Besides this patients are followed during their daily activity through a worn body sensor network. However, although the novel Kinect system makes reliable body tracking generally possible, it does produce poor results in tracking feet that, however, is fundamental in many rehabilitation programs, as regaining postural control and gait is the first request of any patient after a stroke event. We will show here how through combining level set with object representation inside embedding spaces of low dimensionality and parallel processing on GPU, a robust real-time tracker can be built. Exergames are complemented with a novel analysis of motion pattern to derive activity profiling that can be used by the clinicians to tune the therapy and shown to the patient to increase his motivation. The HS is two-fold: it is used by clinicians as a therapy management tool and it supports a virtual community of all stakeholders to increase motivation, ease isolation and increase compliance to the therapy. The Web2.0 technology adopted makes these two components extremely flexible and portable. The NS is installed at the health provider site, at a regional level. It provides advanced data mining functionalities to discover patterns in rehabilitation treatments among hospitals and regions.

16.1 Introduction

Once discharged from hospital, systematic daily monitoring of a patient's recovery of function and movement during rehabilitation has been regarded as infeasible because of the cost and complexity of human motion capture apparatus—apparatus typically suited to the hospital laboratory but not to the patient's home. This landscape has been transformed recently by the introduction of mass-produced but highly capable devices designed principally for the home entertainment market. Devices such as the Nintendo balance board, and the Microsoft Kinect, have been shown to be able to track human motion in real-time and with an accuracy commensurate with the needs of rehabilitation [8, 9]. It has been quickly realized too that the combination of these devices with game-playing could be a very good tool to address prolonged rehabilitation. A games framework can turn the repetitive movements demanded by rehabilitation exercises into an entertaining and amusing activity for the patient, and turn "dry" clinical goals into patient friendly player-oriented goals [23, 30, 35].

Clinicians have already started experimenting with commercial games available for the fitness market, like wii-fit [30, 53, 59], and with games especially developed to guide patients through exercises [5, 6, 70], all with promising results. However, many in this latter set of non-commercial games are rather simple, display poor graphics, and do not maximize engagement by failing to follow the "good rules of game design" [58]. In both sets, the functionalities required to support rehabilitation at home are missing: a continuous monitoring of the correctness of the motion is fundamental to avoid the patients develop maladaptation that might induce joint pain [53]. Automatic feed-back to the patient is required for several tasks: inviting him to the therapy, summarizing the results, advising him when maladaptation occurs, encouraging and so forth. This is the more important when rehabilitating at home, as there no real therapist sitting with the patient. Moreover, as already recognized by several approaches [10, 38, 70], adaptation of the game challenge level should be matched to the exercise difficulty and to the actual patient status.

In this chapter we describe progress in the area of home-rehabilitation for stroke patients made by the EU-funded REWIRE project (http://www.rewire-project.eu). The overall system architecture include three principal components: (1) a patient station (PS) deployed at home (2) a hospital station (HS) installed at the health provider site, and (3) a networking station (NS), again installed centrally (Fig. 16.1). There are several areas of challenge associated with each.

The PS includes several devices to track the patient's body motion. The patient sees on a display either himself or an avatar moving and interacting in real-time with a virtual game environment. We describe an Intelligent Game Engine for Rehabilitation, IGER, that translates clinical demands into a player-oriented set of exercises, and which includes features based on computational intelligence to supervise the patient. Patient movements are recovered from depth and color imagery captured by a Kinect, but using novel 3D object-based tracking algorithms for limb extremities that are less-well tracked by Kinect's built in software. REWIRE takes further advantage of the patient's being fully connected at home by monitoring day-to-day lifestyle through worn sensors that record activity signals and go on to classify them as a number of eigen-behaviors. This wider monitoring is useful in itself, but also provides a broader context in which to assess progress (or otherwise) in specific rehabilitation exercise games.

But patient monitoring alone will not make rehabilitation at home a reality. Efficient management of the therapeutic plan by the hospital is needed, and in REWIRE this is combined with a taxonomy of the rehabilitation progression that allows an objective choice of the exercise games. This definition and monitoring of the treatment is the main role of the HS in REWIRE. It further supports the

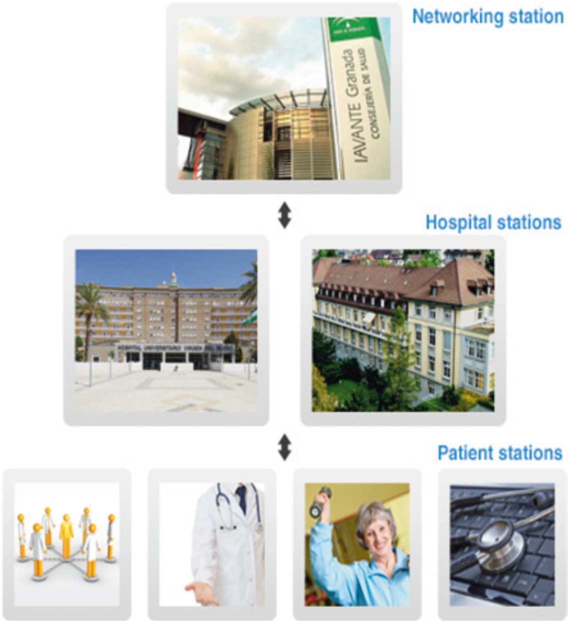

Fig. 16.1 The REWIRE hierarchical approach to rehabilitation that comprehends three stations: the PS deployed at patient's home, the HS and the NS

community of stakeholders: other patients, clinicians, therapists and care-givers can all meet virtually to increase their knowledge, to share best practice, and to ease patient isolation.

Finally, the overall system will acquire volumes of data that can reveal much about the most promising approaches. Data mining in REWIRE's NS uses state of the art machine learning techniques to discover common features and trends of rehabilitation treatment among particular hospitals, geographic regions, and other socio-economic groupings.

The chapter continues by providing some further detail and discussion of the most innovative aspects in these areas.

16.2 Methodology

16.2.1 Rehabilitation Needs

The mainstay of successful neurorehabilitation is training. Successful training depends on intensity that is a combination of the time spent in training and the training demand, i.e., its complexity, difficulty or challenge for the trainee. Moving neurorehabilitation to the patient's home can increase rehabilitation intensity and prolong its duration in time. The simplest form of home-based rehabilitation is homework exercises. With these exercises training demand is often low because of the patient's motivation and compliance, and it precludes highly demanding training. In addition, high demand poses safety risks. Hence, the REWIRE home-based training program is designed to combine high training duration with a proper level of challenge while keeping the exercises motivating, safe and supervised.

If long training duration is the goal, the training has to be entertaining, hiding the burden of repetitive exercises under the hood of compelling fantasy. To maximize engagement, exercises should be at an adequate challenge level: if the training task is too difficult it will be frustrating, if too easy it will be boring. Because it is expected that patients will improve, the training has to be progressive to keep the demand constant, as the trainee gets better. Moreover, exercises can be rendered more complex by adding elements that divert attention. It is known that the ability to maintain balance and to solve a cognitive task at the same time declines with age. This is why elderly people have problems maintaining a conversation while walking. Training that combines exercises with cognitive tasks (dual task training) is specifically apt to improve motor ability [68]. Progression along this dimension of complexity is implemented into the REWIRE training program.

Safety is a concern when training at home is unassisted by a therapist or caregiver. First-line safety issues are device-related, i.e., the subject must not be harmed by the device itself or be motivated to engage in harmful activities. For balance training, falls are the biggest concern. Therefore, training complexity and demand should be optimized under the constraint that safety is maintained. Only by continuous motion monitoring dangerous situations can be recognized and prevented. In the REWIRE system such monitoring is enabled by the Kinect 3D motion monitor.

Second-line safety relates to the training/acquisition of harmful movements. For patients with a paresis, for example, some movements will induce or aggravate spasticity or will over-load joints inducing pain and cartilage degeneration [53]. Encouraging the subject to perform these movements may worsen his impairment by inducing a form of detrimental plasticity that leads to consolidation of false movement patterns. Measures have to be taken to prevent these movements by giving the subject feedback on how to move correctly. In many cases, however, detrimental movement patterns are highly individual, i.e. while a certain movement may be harmful to some it may be fine with other patients. The therapist therefore has to test and verify exercises while the patient is supervised in the clinic before allowing their use at home. In addition, continuous monitoring of the patient is required at home to prevent him using these patterns. This is implemented in the REWIRE PS through a fuzzy based engine that prevents harmful training.

The decision when to end home-based training (like neuro-rehabilitative training in general) is a difficult one. Theoretically movement therapy should only be ended if the patient can achieve sufficient levels of active arm or leg use in daily life serving as a form of self-training. If the patient cannot perform, disuse will lead to deterioration without therapy [61]. Therefore a form of lifestyle activity monitoring is implemented in REWIRE to assess the level of activity during off-therapy hours. The results of monitoring are transmitted to the hospital station where the clinician that leads the home-training program, can perform the necessary adjustments to the training program.

16.2.2 Exergame Design

A rehabilitation session is made up of a mix of exercises that often involve both coordination and strength [29]. Recent findings indicate that balance and muscle strength are important determinants of walking performance [14], and as a consequence, treatment programs should include exercises aimed to improve these components.

Exergames[1] are a convenient way to guide the patients through the exercises. Weiss and colleagues [25] suggest that virtual reality platforms provide a number of unique advantages over conventional therapy in trying to achieve rehabilitation goals. First, virtual reality systems provide ecologically valid scenarios that elicit naturalistic movement and behaviors in a safe environment that can be shaped and graded in accordance to the needs and level of ability of the patient engaging in therapy. Secondly, the realism of the virtual environments allows patients the opportunity to explore independently, increasing their sense of autonomy and independence in directing their own therapeutic experience. Thirdly, the controllability of virtual environments allows for consistency in the way therapeutic protocols are delivered and performance recorded, enabling an accurate comparison of a patient's performance over time. Finally, virtual reality systems allow the introduction of "gaming" mechanisms into any scenario to enhance motivation and increase user participation [20]. The use of gaming elements can also be used to take patients' attention away from any pain resulting from their injury or movement. This occurs the more a patient feels involved in an activity and again, allows a higher level of participation in the activity, as the patient is focused on achieving goals within the game [57]. Such immersion in gaming is known as state of *flow* [11, 12] in which the patient even forgets that he is doing rehabilitation being totally focused on gaming.

In order for the exergames to be effective it is important to explicitly consider two fundamental motor learning principles known to positively affect rehabilitation and, hence, these principles should be considered in developing them. The first principle is task variability [60]. Task variability is a funda+mental principle in terms of retaining learning over time and there is agreement in the literature indicating that varied practice is superior to repetitive single tasks when it comes to motor learning [26]. The second principle is progression. This principle implies that motor learning and rehabilitation programs benefit from a continuous adaptation of task difficulty to increasing skill level [15]. From these two motor learning principles it follows that rehabilitation programs should contain a constallation of exercises, the difficulty of which is progressively adapted to the skill level of an individual patients.

Such progression is well captured by **Gentile's Motor Skills Taxonomy** [17, 37]. A notable feature of the motor skill classification taxonomy proposed by Gentile is the two-dimensional approach. Two dimensions are systematically defining physical

[1] Exergaming is a term used for video games that are also a form of exercise [62].

actions: (1) *environmental context* and (2) *function of the action*. *Environmental context* refers to the environmental conditions to which the patient has to react in order to successfully perform a motor task. This dimension is characterized by (1a) *regulatory conditions* and (1b) *inter-trial variability*. The *regulatory conditions* indicate the relevant environmental features that constrain movement execution and these may be stationary (*stationary regulatory conditions*) or moving (*in-motion regulatory conditions*). With the indicator *inter-trial variability*, Gentile's taxonomy differentiates between regulatory conditions that change between trials (*inter-trial variability*) and those that do not (*no inter-trial variability*).

The second dimension, *action function*, is also characterized by two indicators: (2a) *body orientation* and (2b) *object manipulation*. *Body orientation* indicates whether an action requires the performer to move from one location to another (*body transport*) or not (*body stability*). *Object manipulation* indicates whether an object has to be controlled during the action performance (*object manipulation*) or not (*no object manipulation*).

Through the interaction of the resulting four environmental context characteristics and four action function characteristics, 16 different skill categories can be defined that provide a comprehensive template to classify motor skills (Table 16.1). Each category is associated with unique features and poses qualitatively different demands on the performer. The 16 skill categories included in Gentile's taxonomy are positioned in such a way that simple action conditions are followed by more complex action conditions, with the simplest skill category at the top left position. The task difficulty increases throughout the consecutive 16 categories and the most challenging action situation is placed at the bottom right of the table. Accordingly, Gentile's taxonomy allows a systematic progression in difficulty of physical actions.

Each category is mapped on a set of exercises and we will illustrate here some exercises for balance rehabilitation mapped on Gentile's taxonomy. According to it, the first phase of a rehabilitation program should focus on basic skills. For balancing, this skill is maintaining the body's center of pressure (COP) centered between the two feet while standing quietly. Patients have often problems in achieving this goal as they tend to rely more on the unimpaired leg. This exercise can be guided by exergames that show on a computer screen the position of the COP within a predefined marked circle [43]. Subsequently, the cursor can be moved repetitively from the left to the right edge of a rectangle displayed on the screen [33, 43] to guide them to relearn controlling balance while moving. Such exercises are propedeutic to start regaining stable walking. We explicitly remark that to correctly execute these exercises, patients must maintain a stable straight posture. Appropriate exergames for the early stages of stroke rehabilitation should feature a stable environmental context by adopting stationary regulatory conditions. For the later stages of stroke rehabilitation, we designed exergames that incorporate moving external elements (i.e. in-motion regulatory conditions) and hence present a more challenging environmental context. More specifically, we include exergames that require the catching of virtual dropping fruits or flying darts [1]

Table 16.1 Gentile's taxonomy of motor skills (adapted from [37])

	Gentile's taxonomy of motor skills			
	Action function			
	Body stability		Body transport	
Environmental context	No object manipulation	Object manipulation	No object manipulation	Object manipulation
	1A	**1B**	**1C**	**1D**
Stationary regulatory conditions and no intertrial variability	Body stability No object Stationary regulatory conditions No Intertrial variability *e.g. Standing still with center of mass in between the feet*	Body stability No object Stationary regulatory conditions No Intertrial variability *e.g. Standing still while moving a virtual net with the arm to catch butterflies*	Body transport No object Stationary regulatory conditions No Intertrial variability *e.g. Step laterally to estinguish a fire with boots on your feet*	Body transport No object Stationary regulatory conditions No Intertrial variability *e.g. Step laterally to estinguish a fire pouring water from a virtual bucket on the head*
	2A	**2B**	**2C**	**2D**
Stationary regulatory conditions and intertrial variability	*Body stability* *No object* Stationary regulatory conditions Intertrial variability *e.g. Weight shift over 360° to burst bubbles inside a virtual soup*	*Body stability* *No object* Stationary regulatory conditions Intertrial variability *e.g. Weight shift over 360° to estinguish a fire pouring water from a virtual bucket on the head*	*Body transport* *No object* Stationary regulatory conditions Intertrial variability *e.g. Raise one foot to let virtual animal running go under the foot*	*Body transport* *No object* Stationary regulatory conditions Intertrial variability *e.g. Sit-to-stand to ride a horse and sit-down to avoid high branches from trees*

(continued)

Table 16.1 (continued)

	Gentile's taxonomy of motor skills			
	Action function			
	Body stability		Body transport	
	3A	**3B**	**3C**	**3D**
In-motion regulatory conditions and no intertrial variability	*Body stability* *No object* Stationary regulatory conditions No intertrial variability *e.g. Shift weight laterally to drive a tractor through a field*	*Body stability* *No object* Stationary regulatory conditions No intertrial variability *e.g. Shift weight laterally and move arms to feed a virtual cow*	*Body transport* *No object* Stationary regulatory conditions No intertrial variability *e.g. Raise and pose one foot at a time to manouvre a pump to inflate a tyre of a tractor*	*Body transport* *No object* Stationary regulatory conditions No intertrial variability *e.g. Step laterally and move a virtual net with the arm to catch butterflies*
	4A	**4B**	**4C**	**4D**
In-motion regulatory conditions and intertrial variability	*Body stability* *No object* Stationary regulatory conditions Intertrial variability *e.g. Shift weight laterally to collect fruit falling from a tree.*	*Body stability* *No object* Stationary regulatory conditions No intertrial variability *e.g. Shift weight laterally and move arms to feed one of several virtual mooing cows*	*Body transport* *No object* Stationary regulatory conditions No intertrial variability *e.g. Step over 360° to pop under the feet virtual baloons moving randomly*	*Body transport* *No object* Stationary regulatory conditions No intertrial variability *e.g. Step laterally and move a virtual net with the arm to catch butterflies moving randomly*

to induce weight shifts in the mediolateral direction when catching falling fruits and in the anteroposterior direction when catching flying darts. To meet patients' needs in the final stage of recovery, the rehabilitation program should include advanced stepping tasks in addition to the more basic weight shifting tasks. Specifically, we created scenarios in which virtual obstacles have to be overstepped or dancing steps have to be performed. Such exergame-based circumstances that demand stepping tasks present some examples of skills that involve body transport. As it can be seen, several exer-games can be used in different boxes to guide exercises with different requirement and difficulty.

As described in the methods section, Gentile's taxonomy involves skill categories that require the manipulation of an object (i.e. object manipulation). To meet this requirement, some of our exergames include object-manipulating tasks. In such games, patients balance a virtual water container on their heads or a basket filled with fruits. In order to avoid water spillage or to prevent fruits from falling down, they must adopt an ideal upright body posture. In another game that involves manipulating an object, patients are holding a virtual net in their hand to catch butterflies whilst maintaining standing balance. We remark here that main goal of such exercises is not exercising physical coordination but, through paying attention to the performance of physical exercises, they are expected to train cognitive skills [48]. Deficits in attention correlate with functional impairments and falls in stroke survivors [21] and should, consequently, also be part of post-stroke rehabilitation.

An exergame can be played at different levels of difficulty. The difficulty level of the exercise is based on Fitts' Law. According to this law, speed and accuracy are crucial aspects when performing motor skills and both components determine the index of task difficulty [70]. By restricting the maximum time allowed to complete an exergame and by decreasing the size of virtual targets that have to be reached through patients' COP displacements, task difficulty is increased and COP control remains adequately challenged at increasing skill levels. This allows defining several difficultly levels that can be chosen by the therapist according to patient's ability.

As it is clear from above, a rehabilitation program is constituted of a constellation of exercises and the difficulty of each of them should be adapted to the patient's status. Moreover, each exercise consists in repeated movements and actions that aim at stimulating the recovery of the impaired function. Different patients have varying degrees of impairment and this requires that each exercise is tailored specifically to their residual abilities.

The exergames should meet these requirements: not a single game, but a constellation of games is required to implement a whole rehabilitation session. Moreover, given the time span of the rehabilitation, a progression should be available, by choosing different exergames or making exergames more difficult. For the latter, exergames need to be fully parameterized so that they can be set-up by the therapists for each specific patient setting the value of a few adequate parameters, such as the movement range or speed of targets [19, 39, 49]. On the other side, monitoring the correct execution of the exercises and giving an automatic

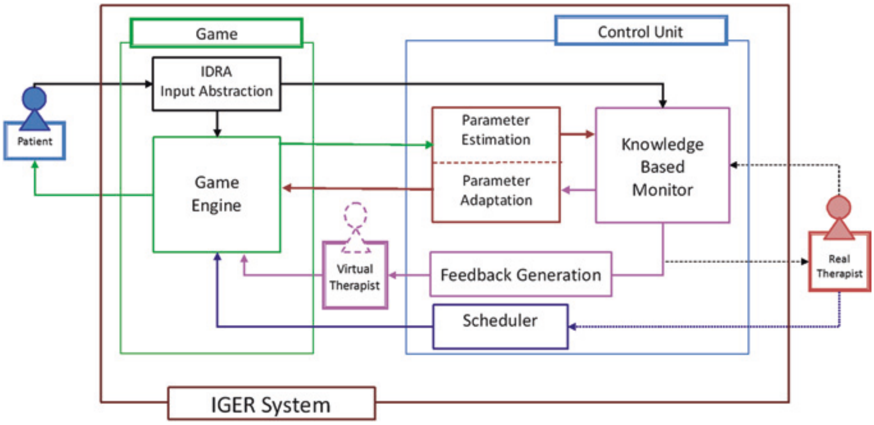

Fig. 16.2 The IGER structure. The Control unit has been added on top of the Game Engine. The IDRA layer allows using many different tracking devices

feed-back to the patient while exercising is equally important when home rehabilitation is considered.

16.2.3 IGER Structure

This calls for the realization of a game engine that realizes monitoring, adaptation and feed-back on one side and on the other side it makes the realization of exergames that implement **the** exercises easier. We describe here the last developments of the Intelligent Game Engine for Rehabilitation (IGER, Fig. 16.2) developed for this goal [4, 49].

IGER is built on the top of a classical game engine (Panda3D, http://www.panda3d.org/, is used here but other game engines like Unity3D, http://unity3d.com/, can be used as well) extending it through Python script **language** such that additional features, tailored to rehabilitation are provided to the exergame designer besides standard features provided by a standard game engine: scene loading, input handling, animation, collision detection and graphical rendering. Additional features provided by IGER are: games configurability, real-time adaptation and monitoring, feed-back and data log (Fig. 16.2). Without these additional components the effectiveness and reliability of any exergame for rehabilitation at home can be severely questioned. Moreover, these additional components cannot be developed as standalone but should work in synergy: for instance, monitoring modulates real-time adaptation, inhibiting it when wrong movements occur.

Adaptation is implemented at two levels. It is available at the hospital site to program the level of difficulty of the exercise defining one of several possible level of difficulty of the games (configuration). The difficulty level of the exergame can be further tuned during gaming as suggested in several papers [6, 10, 34, 49, 66, 70] with the aim to achieve the maximum engagement of the patient. To achieve this a Bayesian framework has been developed for REWIRE in which no hypothesis a priori, model or heuristics is required and therefore it allows the most general solution to adaptation. The basic idea is to monitor the game outcome in terms of success/fails and move the threshold such that this rate is moved towards a pre-defined score (e.g. 80 %). Such shift of the threshold is mitigated by the starting threshold set by the clinicians at the hospital [4].

Monitoring is implemented through a knowledge based fuzzy system. A therapist defines at the hospital the constraints on motion or posture that have to be satisfied to avoid maladaptation: while exercising the patient is continuously monitored by IGER: incorrect movements and posture attitude, especially in patients that do have one side of the body weaker than the other, not only prevent recovering functionality in the hemi-paretic side, but also tends to increase stresses and forces on the not paretic side increasing the possibility of bony and cartilage damage that manifests as pain [53]. For each constraint a maximum value is defined and the range between zero and maximum is fuzzyfied into four classes: zero, mild, medium, serious. During gaming IGER receives the inputs from the tracker and checks them against the rules through a fuzzy engine [49]. Each rule activates an alarm level that ranges from zero to high level depending on the degree of activation of each rule. All alarms levels are sent to the feedback module that decides further action. At the same time a medium level alarm prevents any further increase of game difficulty and a high level alarm induces a decrease in game difficulty. The alarm level is also logged to be examined by therapists in the hospital.

The feed-back module sends an immediate a qualitative feed-back to the patient by means of a color change of the avatar's body part that is violating the rule (cf. Fig. 16.9). For instance, if the patient is tilting his back during an exergame, the avatar's back would change the colour from green to yellow, orange and then to red in the most severe cases. When the highest level of alarm is reached the game is paused and the patient is given advice about the correct execution of the exercise through her virtual therapist (cf. Fig. 16.10). A timer prevents the therapist to be shown too often making impossible to progress in the exercise. The same virtual therapist is used to introduce the rehabilitation session and to guide the patient.

The game engine is complemented with the use of Natural User Interfaces (NUIs) that allow the user to interact with the game and with the menu through speech or gestures, forgetting of the PC for the entire duration of the rehabilitation session. We have used here the functionalities of the Kinect SDK to achieve this task. It is used in combination with Google translator that allows a conversion text to speech of good quality.

We explicitly remark that a game engine for rehabilitation should be able to interface many different devices that can be used alone or in combination for different disfunctions. We use Kinect as a master device as it provides NUI functionalities and many other devices can be used in combination: Nintendo Wii balance board, Tyromotion Timo plate, Sony PS3 cam, Novint Falcon phantom, Moticon insoles and PA10 robotics arm have all be successfully used as input device. This is made possible by a middleware, named IDRA (Input Devices for Rehabilitation Abstraction layer), designed to match the input streams required by each game to the output data stream provided by the devices. Moreover, it avoids conflicts between multiple devices and allows users to play all games regardless of the chosen device.

16.2.4 Patient Tracking

The role of the patient tracking module in REWIRE is to recover elements of the patient's pose, and feed these back to the IGER so that the patient can view himself (or an avatar) moving on a display within the game's environment. Three key requirements are (1) that that the sensing set-up is applicable to the home environment; (2) that feedback is returned at high rate and with low delay to avoid instability; and (3) that the limb tracking satisfies clinical demands. The Microsoft Kinect with its two synchronized 30 Hz cameras, one delivering conventional colour (RGB) imagery and the other an IR camera delivering depth (D) imagery, together with its SDK which reconstructs skeletal pose, go a considerable way to meeting these requirements, but two principal challenges remain. First is the need to develop improved calibration tools. The second is that detailed tracking of limb extremities is required, particularly of lower limbs and feet. The Kinect's SDK alone struggles to provide stable and accurate information about these body areas.

Our approach to the tasks of calibration, 3D limb pose tracking and 3D model building is a unified one. Throughout we use dense RGB-D image data to recover scene information via optimization of cost functions based on level sets, as developed for conventional imagery in 2D by Bibby and Reid [2, 3] and in 3D by Prisacariu and Reid [51, 52].

16.2.4.1 Calibration Through Tracking

After correction for radial distortion, both the Kinect's depth and colour cameras can be modeled to first order by central projections with (homogeneous) projection matrices $\boldsymbol{K}_d[\boldsymbol{I}|\mathbf{0}]$ and $\boldsymbol{K}_c[\boldsymbol{R}|\mathbf{t}]$, where the 3×3 $\boldsymbol{K}$ matrices describe the 5-dof intrinsic calibration and $\boldsymbol{R}$ and $\mathbf{t}$ give the rotation and translation between the camera coordinate frames. The depth camera defines the world frame. A scene point $\mathbf{X} = [X, Y, Z]^\top$ is imaged in the depth camera at position $[x, y]$ with pixel brightness encoding the depth Z recovered from structured light calculations. It is straightforward to show that $\mathbf{X}$ can be recovered from: $\mathbf{X} = Z\boldsymbol{K}_d^{-1}\left[x, y, 1\right]^\top$ once $\boldsymbol{K}_d$ is known.

First assume that $\boldsymbol{K}_d$ is known, and consider an object B wholly contained within a voxelized object space, as sketched in Fig. 16.3a. For any point $\mathbf{X}^B$ in that space, the *signed distance function* Φ is the shortest distance from $\mathbf{X}^B$ to the

Fig. 16.3 **a** The voxelized space around an object. In practice the volume is 384 × 384 × 384 voxels. **b** An object being tracked during calibration. The calibration parameters converged after some 300 frames, or 10 s of movement

surface of the object, signed positive when outside and negative when inside. The object surface is thus defined implicitly by $\Phi(\mathbf{X}) = 0$, the zero-level set [45]. Postulating the pose $\mathbf{p}$ of tracked object allows measured scene positions $\mathbf{X}$ to be transformed into the object space by a Euclidean transformation $\mathbf{X}^B = \boldsymbol{E}(\mathbf{p})\mathbf{X}$. A robust cost function is defined as $\mathcal{E} = \Sigma\Psi(\mathbf{X})$, for all $\mathbf{X}$ transformed into the object voxelized space, where $\Psi = \Phi^2/(\Phi^2 + \sigma^2)$ and σ^2 determines the width of the basin of attraction in this Geman-McClure function. Voxelization speeds this up by allowing a pre-computed Φ value to be used for each each occupied voxel. A gradient-based optimizer, specifically Levenberg-Marquardt [32, 41], is used to minimize $\mathcal{E}$ with respect to changes in the pose $\Delta\mathbf{p}$. By off-loading heavy computations to a GPU, this 6-dof tracking takes some 20 ms per frame on a 640 × 480 depth image.

When the intrinsic matrix $\boldsymbol{K}_d$ is not known a priori, the same approach is used but the cost function is minimized not only with respect to pose change, but also to the five calibration parameters, the focal length, aspect ratio, principal point and skew. Simultaneous tracking and calibration with 11 parameters increases computation time to some 30 ms per frame. The patient's role is to move a known 3D calibration object made of light foam in front of the camera for around 10 s. Figure 16.3b shows the object being tracked during a calibration run. Further details and results are given in Ren and Reid [54].

A further calibration involves the recovery of the rotation $\boldsymbol{R}$ and translation $\mathbf{t}$ between RGB and D cameras. $\boldsymbol{K}_d$ is known, but $\boldsymbol{K}_c$ must first be recovered using the classic tile method [31]. Then a sphere is tracked in both cameras giving trajectories of n corresponding points $\mathrm{x}_d = Z\left[x_d, y_d, 1\right]^\mathsf{T}$ and $\mathrm{x}_c = \left[x_c, y_c, 1\right]^\mathsf{T}$ related by $\lambda\mathrm{x}_c = \boldsymbol{K}_c\boldsymbol{R}\boldsymbol{K}_d^{-1}\mathrm{x}_d + \boldsymbol{K}_c\mathbf{t}$ where λ is a per point scaling. The optimum extrinsics are found by minimizing the 2-norm of the reprojection error $\sum_{i=1}^{n} \mathrm{x}_{ci} - \hat{\mathrm{x}}_i(\boldsymbol{R}, \mathbf{t}, \mathrm{x}_{di})^2$, where the x here are inhomogeneous 2-vectors obtained by division by λ. Again, results are given in Ren and Reid [54].

16.2.4.2 Simultaneous Tracking and Reconstruction

A calibration object must have a known fixed shape, but for foot and hand tracking in REWIRE the shape model needs to be derivable at the patient station and so the object shape Φ must now be treated as a variable. To augment the shape model,

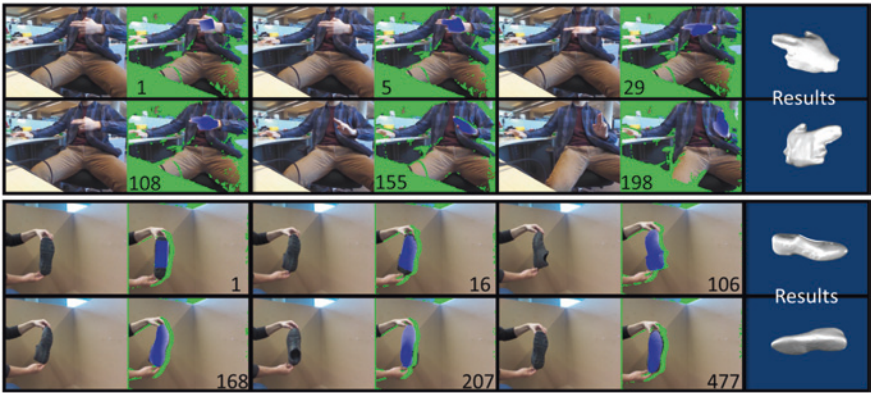

Fig. 16.4 Film strip showing tracking and reconstructing a moving hand and shoe. For each frame, *left* shows the color image while *right* shows the reconstruction result overlayed with the color image re-projected onto the depth image. Green indicates missing depth data

two histograms describing object and background colour are also updated. The shape Φ generates within the voxelated cube a set of positions $\mathbf{X}^B$, each labelled as either outside, inside, or upon the object's surface. Setting a pose $\mathbf{p}$ then allows not only the depth image but also a histogram corresponding to the color image to be generated.

Given a sequence of RGB-D images $\Omega_o, \ldots, \Omega_k$ of a moving object, the aim is to find both the optimal poses $\mathbf{p}_0, \ldots, \mathbf{p}_k$ of the object, along with optimal shape of the object defined by its zero level set. Given a set of RGB-D images we wish to maximize the conditional probability $P(\Phi, \mathbf{p}_0 \ldots \mathbf{p}_k | \Omega_o, \ldots, \Omega_k)$ re-expressed using Bayes' theorem as as a MAP estimate involving a product of the likelihood of generating the imagery and the pose and shape priors. As shown in Ren et al. [55], despite the number of obvious independences in the probabilistic model, full inference is intractable. Instead periods of Maximum Likelihood estimation are carried out for the object poses given fixed shape Φ, followed by periods of MAP estimation for the shape, assuming the poses are known and fixed. The shape model is initialized as a sphere, and the color model from an initial motion segmentation. Figure 16.4 shows examples of simultaneous tracking and reconstruction for a hand and shoe.

16.2.5 Assessment of the Exercises and Support to Patients Through a Virtual Community

The HS has been designed as a web application that works as a Therapy Management tool for clinicians and therapists (Fig. 16.5a). The HS is run by clinical staff at the hospital and helps them to define, tune and monitor the rehabilitation program

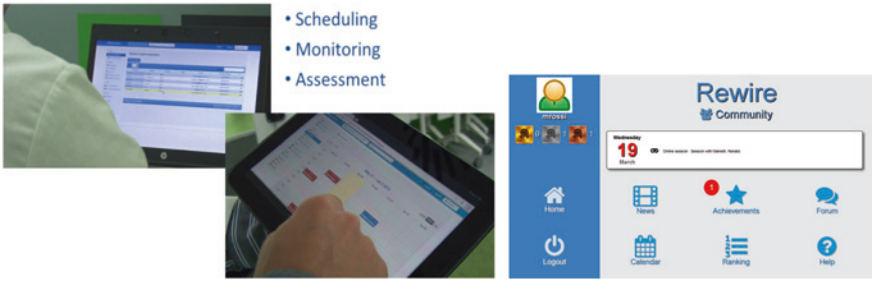

Fig. 16.5 The HS therapy management tool run on a palmtop (*left*). The PS community graphical user interface (*right*). It can be browsed with a mouse or with recognition of gesture tracked by the Kinect camera

exercises, which will be executed by patients at home. It allows maximizing the agreement on the therapy that is one of the key factors to maximize patient's compliance [36, 63]. To this aim, the HS allows clinicians to choose, for each day, a subset of exer-games and the associated difficulty level and duration. The choice will be based on the current position inside the Gentile's taxonomy: not only the exergaming data previously collected by the PS during the exercises are taken into account but also the data collected by a network of attached body sensors (Body Sensor Network) that monitors daily free activity (see Sect. 16.2.6).

Exergames data constitute the documentation of rehabilitation activity. Once a rehabilitation session is completed by the patient, the PS sends the exergaming data to the HS where they are processed to provide to the therapists the most adequate graphics and tables that portray the results of rehabilitation sessions in more visual way. The HS implements a two-step granularity through two kinds of reports: session report and aggregated therapy report. In this way the clinicians can consult the more detailed results of some particular session and also make a global look on the patient progress and therapy effectiveness through an aggregated report. To this aim, the HS provides also features which allow the users to filter, classify and order the outcome shown on the screen. The results are represented with the most important metrics related with rehabilitation treatment concepts, like, for instance, the exercise level, the level baseline, the level objective, the body segments orientations, the COP variability and so forth. These data can also be used to replay the whole session or one single exercise. Overall, the data portray the rehabilitation outcome to the therapist who can evaluate the rehabilitation effectiveness, advice the patient and possibly tune the therapy. Based on this information, the clinicians make also the decision about patient progression inside the Gentile's taxonomy. The same parameters can be shown to the patient at the end of each session, along with the value obtained in the previous sessions, as a feed-back on his effort. The HS supports also a virtual community of all the stakeholders (patients, therapists, caregivers, clinicians) through Web2.0 tools (Fig. 16.5b). It will be used by the patients and caregivers inside the Patients Station (PS) or on any other portable device, and by the medical staff from the hospital inside the Hospital Station (HS). Such social dimension is considered fundamental to promote social and active lifestyle on seniors increasing their motivation and compliance [24, 44]. The community offers patients access to different information resources (news, forum, etc.) about their pathology as well as provides interaction with all the stakeholders. This encourages more patient empowerment and motivation: patients are increasingly involved in self-management of their own care. This has a positive effect on their mood and encourages them to follow rehabilitation therapy.

Moreover, the platform will progressively store valuable content that will be returned to the uses a shared knowledge about physical, social and clinical information related to patients' diseases, beyond the one-to-one communication with their reference physician [36]. The clinical staff also will have the possibility to use the community to share clinical information about diseases and exchange opinions with their pairs through comments or forum.

16.2.6 Assessment of Rehabilitation Effectiveness Through Everyday Life Activities

The restoration of the functional independence is the ultimate goal of an effective rehabilitation program since the improvement of motor and balance function, gait and independence in performing daily-life activities are associated with better quality of life (QoL). For stroke patients, an accurate and objective assessment of motor function and physical activities during everyday life is important to match patients to the appropriate exercises and for documenting the outcome of rehabilitation.

Usually, the evaluation of rehabilitation is based on the observations of the participants' motor behavior using standardized clinical rating scales. The accuracy and consistency of observational assessments may vary greatly across clinicians. Wearable sensors configured as Body Sensor Network could be used to provide more objective measures or could be used in addition to observational clinical tools. The main advantage of wearable technology is the ability to measure motor behavior under real-life conditions and for longer periods than could be observed in a clinical setting [47]. However, there are a number of requirements that need to be considered for the design of a lifestyle monitoring system in the context of stroke population.

The monitoring devices need to combine two important features, which are the miniaturization and the multi-sensing capability. This signifies that the devices must be small and lightweight in order to avoid interferences with the movement features and activities of daily living. At the same time, they need to incorporate sensors to capture the 3D body kinematical features, electronics for data acquisition and batteries for long-term power supply. Additional sensors to monitor physiological parameters (e.g. heart rate) and environmental parameters (e.g. temperature, humidity, barometric pressure) may add valuable information in the context of stroke rehabilitation in home settings. The REWIRE lifestyle monitoring system was designed to fulfill these requirements [42].

In addition to the hardware specifications another important issue is the development of analysis methodology capable to provide a comprehensive assessment of daily functioning before, during and after the rehabilitation process. The reliable quantification of the specific level of impairments in the trunk, upper limbs and lower limbs allows determining the extent to which each might influence the ability to perform the activities of daily living. Using a defined sensors configuration (e.g. upper and lower limbs, trunk) the REWIRE lifestyle analysis algorithms provide a set of outcome parameters related to the various aspects of motor function.

Balance and postural stability are assessed from the acceleration of the center of mass (COM) [69] and the kinematical features of the trunk during postural transitions (sit-to-stand/stand-to-sit) [16]. Progressive usage of the upper limbs are evaluated from the: (1) range of motion (2) motion speed and motion smoothness (3) dominant upper-limb segment during daily activity [11]. Physical activity is quantified in terms of body postures/activities, i.e., sitting, standing, lying and walking activity Improvement in walking function and gait performance are assessed from the analysis of daily-life walking episodes, to estimate duration, speed, cadence, stride length and gait asymmetry [56]. Finally, the different dimensions of physical activity/motor behavior (type of activity, intensity and duration) are integrated into temporal sequences and analyzed to obtain a representation of frequent activity patterns over time; the identification of such frequent patterns enables the observation of the inherent structure present in a patient's daily activity for analyzing routine behavior ('eigenbehavior') and its deviations [46].

One of the objectives of post-stroke rehabilitation programs is to increase levels of metabolic expenditure by recommending daily moderate exercise activities (specifically during non-rehab days). Ambulatory monitoring of metabolic expenditure which can be derived from accelerometer signals and heart rate provide information on patients' exercise behavior, useful in counseling and tracking the patient progress.

16.2.7 Impact on the Health Provider Side

The rehabilitation of a patient after stroke is a continuous process, presently limited in time, which is based on objectives shared with the patient (reduce disabilities) in order to achieve as much functional recovery as possible that will facilitate the independence and the social and work life integration [7, 28].

Given that European population is getting older[2] the increasing figures of such events are deemed to increase; this poses a large burden to the National Health

[2] In Europe, the share of people aged 65 years or over in the total population is projected to increase from 17.1 to 30.0 % and the number is projected to rise from 84.6 million in 2008 to 151.5 million in 2060. Similarly the number of people aged 80 years or over is projected to almost triple from 21.8 million in 2008 to 61.4 million in 2060 [18].

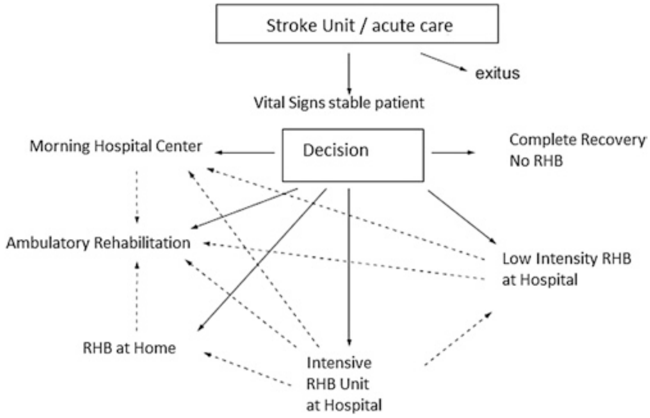

Fig. 16.6 The diagram of conventional rehabilitation process and network

Service Providers that become overly saturated and are forced to shorten the duration of the rehabilitation service, increasing the period in which subjects rehabilitate outside the hospital. However, stroke patients, also after being discharged from the hospital, have to do physical and cognitive exercises regularly to further improve function, reduce disability and dependence on nursing services and to stabilize their psychophysical condition.

This is supported presently by a network (Fig. 16.6) that includes: Rehabilitation available models include: (a) Intensive rehabilitation programs at hospital. (b) Low rehabilitation programs at hospital. (c) Ambulatory rehabilitation programs at hospital. (d) Morning hospital center. (e) Rehabilitation at home. Each patient is treated by a multidisciplinary team lead by a reference clinician. This identifies with the patient the objectives that the patient wants achieve, describes the interventions and measures the results during and at the end of the rehabilitation process. Although the National Health Provider resources are not distributed uniformly throughout the rehabilitation network, their use is aimed at guaranteeing to the patients easiness to access and appropriate care settings to ensure the intensity, specificity and technology to achieve maximum effectiveness and efficiency in the results.

Although the selection on the most appropriate rehabilitation program should be individualized and should involve the patient and his family, there are specific clinical, social and family profiles most appropriate for each rehabilitation area that optimizes rehabilitation program outcomes. The selection criteria should be based on the type of patient, the required intensity of the rehabilitation program (number of hours), tolerance and resilience to therapy, the definition of necessary rehabilitative therapies, the need for medical and nursing care and family and social support available to the patient. The location of the patient may be changing along the rehabilitation process, but coordination and continuity should continue throughout the rehabilitation period.

In all cases, a rehabilitation program constituted of daily sessions that currently have to be carried out in specialized centers, with the support of therapists. This option can be afforded by few patients as it is often not fully supported by public health systems and lead to an enormous socioeconomic impact also on the patient's families that often feel left alone by the health service providers and patients that should continue the therapy outside the hospital actually drop out mostly due to high costs [28]. This is one of the fundamental challenges that the health care provider must meet and which the technology described here tries to answer.

Aimed of the technology described here is to allow prolonging the intensive rehabilitation period as long as required, eventually for the rest of the patient's life. This will be achieved treating the patients at home with the supervision of the hospital where the rehabilitation progress is periodically checked. As the REWIRE platform is expected to shorten the treatment period at the hospital, an overall reduction of the costs for the National Health Service will be meaningful. However, efficacy and efficiency of the platform should be preliminary carried out. Efficacy can be assessed through double blind clinical trials on homogenous patient population. Efficiency requires a more cautious analysis of the different factors.

The economic evaluation can be defined through the comparative analysis of possible alternatives to REWIRE and it is based on the analysis of benefits and costs. Cost can be factored out into direct and indirect costs. Direct costs include both health resources expenses and health professional time. Several elements have to be considered like treatment: drugs, toxin botulinum infiltration, technical assistance: walking stick, wheel chair, use of the hospital facilities: rehabilitation sessions, treatment room, physiotherapy gym, transportation costs: bus, individual ambulance, collective ambulance, personal taxi, medical consultation. To these costs, health staff time should be added: rehabilitation doctors, physiotherapists, occupational therapists, speech therapists, assistant technicians, secretaries and administratives. Direct costs from the patient side should also be considered like house keepers and accompanying persons. To these costs the costs of the equipment has to be added: software, hardware and network connection and the cost of the technological support. The cost of the technology will take into account useful life of systems and service life as well as the costs of technical staff to manage the software. The analysis will be based on indexes that evaluate the effect of rehabilitation on the quality of life [27]. This will be measured by means of the EuroQOL Quality of Life Scale (EQ5D), by the Stroke Impact Scale (SIS) and by the Quality Adjusted Life of Years (QALY) as effectiveness outcome [50]. These indexes are complemented by a set of standard clinical tests administered to the users at the beginning of the home rehabilitation program, in the middle and at the end. The motor function is evaluated by means of a battery of tests including: Fugl-Meyer assessment, Modified Ashworth Scale (MAS) and Action Research Arm Test (ARAT) for upper limb. Six minutes walking test and Berg Balance Scale can be used for balance and lower limb. Barthel Index, modified Ranking Scale (mRS) and Motor Activity Log will also be computed. Efficiency in terms of economic impact is evaluated by comparing costs of traditional rehabilitation path to the ones incurred by using REWIRE. We propose here to use the following index that expresses the incremental cost-effectiveness ratio (ICER) defined as:

$$ICER = \frac{Cost_{REWIRE} - Cost_{Traditional\_care}}{Effectiveness_{REWIRE} - Effectiveness_{Traditional\_care}}$$

The use of ICT technology to record the rehabilitation and lifestyle data constitute a huge data-base on the rehabilitation history for each patient. With novel ICT technology, the health providers will have the possibility to monitor after-stroke patient's evolution on a large scale and therefore anticipate trends and properly distribute their resources. Knowledge discovery methods can be used to extract useful new knowledge and to learn predictive models both at the level of individual patients and at the level of a patient population in order to help in designing a therapy plan best suited to each individual patient. These models may also monitor risk factors and predict possible occurrence of new episodes. Moreover, these data can be used to monitor the evolution of given pathologies, discover new ways of reacting to rehabilitation sessions and monitoring the evolution of these pathologies in the long run. Outcome of this analysis can produce a model based prediction of resources allocation and government policy.

16.3 Results and Discussion

16.3.1 Rehabilitation Needs and Specifications

To design an effective platform that translates into a working and useful prototype the clinical demand, an adequate design methodology should be used. One of the early challenges in the design and setup of the REWIRE platform was to identify, collect and merge largely different user needs. Indeed, the system has to address patients, clinicians and health administrators, each of them with different background, perspective and expectations on the system itself. A user centered approach [40] was mandatory to guarantee that the deployed system might cope with the users need as one of the main issues in designing innovative products, like REWIRE, is the ability to anticipate the future use of the product itself. The process and tools defined in REWIRE both for functional specifications collection and for outcomes assessment may be replicated in similar studies and applications.

Identification and formalization of the expected users was the first step of the process as different users are characterized by different background\knowledge and different expectations. In particular referring to the patients selection, it was decided to focus on homogeneous populations with clearly defined subsets of rehabilitation needs: for instance, posture and balance, arm, hand rehabilitation in the physical domain, however keeping in mind the need of implementing a very

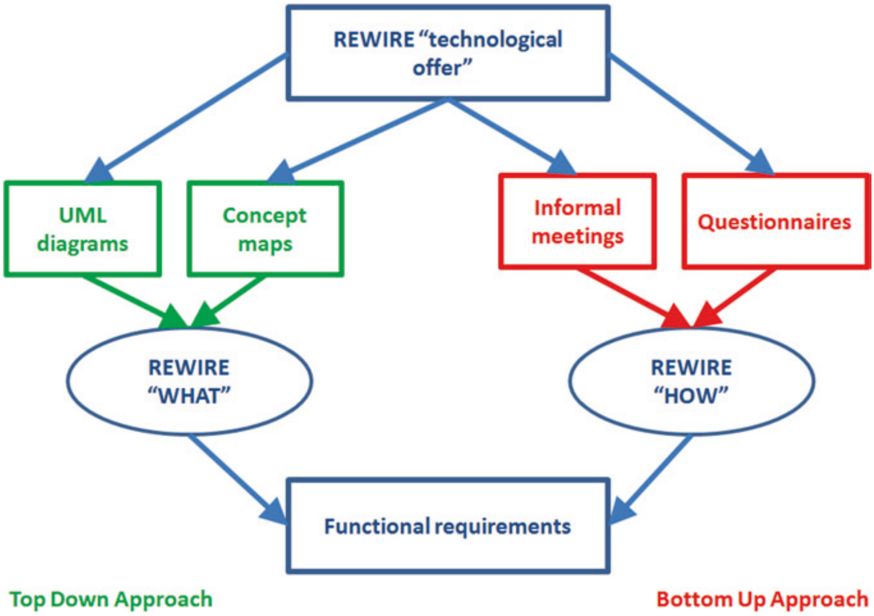

Fig. 16.7 REWIRE design methodology

modular architecture to deliver a system to be easily tailored to other exercise scenarios. Within the selected use case, precise inclusion/exclusion criteria were defined to choose homogeneous candidate users aiming at assessing not only the technology acceptance on an individual basis but also the rehabilitation outcomes on a quantitative ground.

To design REWIRE by matching technology and daily life needs, different sources of information have been used and different methods of analysis have been applied as described in Fig. 16.7. The initial REWIRE concept in terms of "technological offer" was presented to potential users by means of informal meetings and questionnaires (carefully diversified for the specific users subsets, i.e. clinicians and therapists, patients and health administrators) to identify the expected working modalities (the "HOW" of the system) according to a bottom-up approach, while the same technological idea was detailed by the analysts in terms of concept maps and Unified Modelling Language (UML) diagrams to get an exhaustive description of functions (i.e. the "WHAT" of the system) in terms of elementary functionalities by a classical top-down approach.

The REWIRE functional requirements, obtained by merging the results of the two complementary design approaches, were matched to the available technologies and the development process started to develop and setup the REWIRE system as described above. To implement an effective participatory approach, the involvement of end users was not however limited to the specifications collection, but their consideration was required all along the development process by

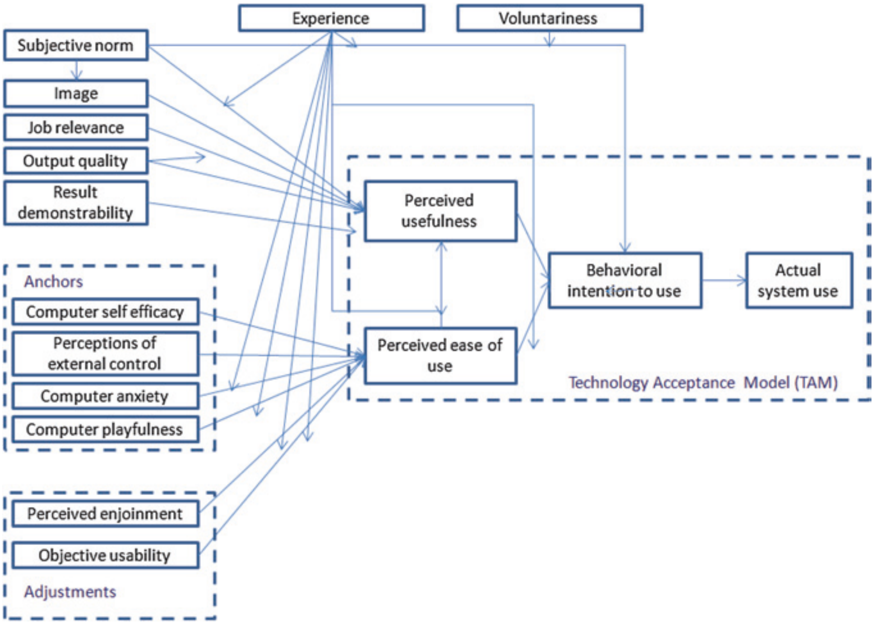

Fig. 16.8 The TAM3 evaluation model [65]

assessing the development outcomes. So, the next challenge to be addressed from the methodological point of view was the identification of suitable tools to evaluate REWIRE according to different use dimensions, namely technological acceptance by the end users (patients, clinicians, therapists and health administrators); efficacy of the system in terms of clinical outcome and efficiency in terms of economic impact.

To assess attitude and motivation of the patients, both in this initial phase and afterwards, during therapy administration, the Technology Acceptance Model (TAM) and its modifications will be implemented. The theory related to TAM was born in late 80s [13] and developed in the following years [64, 65] to get a model of the determinants that affects adoption and use of information technologies (ITs) on the work place. Indeed, the theory is quite flexile and was in the following, also successfully applied to evaluate the adoption of health IT based systems both on clinicians and patients.

TAM builds the prediction of individual adoption and use of IT on two main beliefs that affect the behavioral intention of the individual to use ITs; they are perceived usefulness defined as "the extent to which a person believes that using an IT will enhance his or her job performance" and perceived ease of use defined as "the degree to which a person believes that using an IT will be free of effort" (Fig. 16.8). All the determinants will be assessed by standard validated items. Two devoted questionnaires were specifically developed for clinical personnel and patients. Within REWIRE, part of the determinants will be evaluated at the

Fig. 16.9 In the Fruit Catcher game, the patient has to move laterally (shifting the body weight with the feet still or stepping laterally depending on the exercise) to catch fruits falling from a tree. The color feed-back from monitoring is also shown. In panel **a** the patient is bearing more weight on his *right leg* (monitor on COP) and this is shown to the patient through a *yellow rectangle* below the avatar's right foot. In panel **b** the patient's back and head are tilted laterally (monitor on orientation)

enrolment time (even with selection purposes in terms of assessment of attitude and motivation) and part during the use of the system.

16.3.2 Implementation of REWIRE Components

Several games have been developed with IGER to address posture and balance rehabilitation according to specifications set by the therapist. *Fruit Catcher* (Fig. 16.9) has been developed to train lateral weight shift. The game asks the patient to catch fruits as they fall from a tree, using a basket placed over the head of the player's avatar. The game is played in third person, with the user viewing the scene from behind the avatar's back. The player is required to catch the fruits as they fall laterally in a range specified by the therapist. The *Fruit Catcher* game can be run with two different exercises. For the first exercise (1) the patient is required to shift his body to the left and to the right, while keeping the feet still on the ground. For the second exercise (2) the patient must instead step laterally inside the play area. The game can be played using either a Wii Balance Board, a Tymo Board or the Kinect sensor for the first exercise (1), while for the second exercise (2) only Kinect can be used as a tracking device since foot tracking is required for lateral movement. The *Hay Collect* game (Fig. 16.10a) is also aimed to train lateral shift. It asks the patient to drive a tractor across a field while collecting hay bales. The tractor moves at constant velocity and the patient steer the wheels moving the weight left or right. The *Mix the Soup* game (Fig. 16.10b) was designed to train weight shift in all directions. The patient is required to touch a set of bubbles that appear on the surface of the liquid in a cauldron with a ladle

Fig. 16.10 Some of the other games developed to train balance and posture are shown. **a** Tractor driver. **b** Mix the soup. **c** Horse riding

that is moved shifting the weight over a balance board. A cognitive load can be added by randomly spawning bubbles of different colors and requiring that only bubbles of a given color have to be touched. The *Horse Riding* game (Fig. 16.10c) has been designed for developing strength as it required the patient to stand up and sit down while riding. When standing up the horse rides faster but the patient has to sit down to avoid tree branches on the course.

In the case of at-home rehabilitation, the real therapist is not available and IGER tries to partially replace here through a Virtual Therapist (VT) that provides feed-back similar to the one given in routine sessions by a real therapist. The VT is an avatar that accompanies the patient during his rehabilitation sessions throughout the life of the application and advices him. This character can be useful for multiple purposes: it can explain how to navigate the interfaces and how to play the exergames, it can introduce options, congratulate on achievements and motivate during challenges. It also explains to the patient how to correctly perform the exercises when wrong movements are detected by monitoring. Many entertainment games use similar figures as guides for the player, such as the Wii Fit games (http://wiifit.com/) and their cartoon-like animated balance board. In REWIRE, to maximize the compliance with the patient, the VT can assume several shapes, like an avatar, Hannah (Fig. 16.11a) or a mascotte, Piggy (Fig. 16.11b) whose choice can be made by the patient. Although most patients chose Hannah a few of them chose Piggy as they preferred to have a non-human agent shown on the screen.

Another important functionality provided by IGER is monitoring (Fig. 16.9) that is required to ensure the correctness in the execution of the rehabilitation program. The knowledge based fuzzy system is transparent to the patient who sees only the result in terms of change of color of a body part of his avatar: the patient immediately gets a suggestion on how to improve the quality of his exercise. This feed-back was considered very important by therapists and natural by the patients who were intuitively guided towards making a correct execution of the exercises. This sometimes forced them to slow down the pace of exercising until the avatar remained green or yellow for the entire duration of the exercise.

A proper difficulty level can be chosen at the hospital site by setting adequately a specific parameter. For instance in *Fruit Catcher* when associated to lateral steps, levels are defined by the width of the range from which fruits are spawn: the larger the range the more difficult the game. Besides this, the challenge level can be

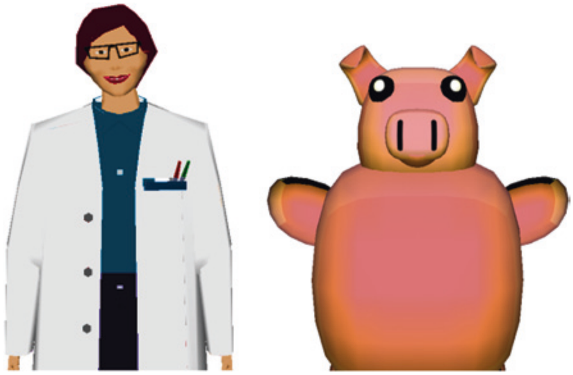

Fig. 16.11 Two virtual therapists used in the IGER system: a humanoid avatar, Hannah (*left*), and a mascot, Piggy (*right*)

further tuned to the actual patient's performance. In *Fruit Catcher* the frequency of spawning fruits can change during game such that a given a success rate, here set to 80 %, is achieved on average. From the point of view of the patient, this allowed to get always a proper amount of challenge, increasing engagement [22, 67]. In *Tractor Driver,* adaptation is carried out on tractor speed by measuring the number of hay bales collected while in *Mix the Soup* the inverse of the lifetime of the bubbles and the frequency of spawning new bubbles increases with the difficulty level. In horse riding, the same speed of the horse determines the level of difficulty. All these modalities allowed to the patient the most natural game experience as they regarded the games as "reasonably difficult".

We have tried to keep a unifying theme for all the games, specifically the *life in the farm* which proposes a calm and reassuring atmosphere. This will be the basis to create a motivational control engine that will allow providing the maximum motivation to the patient and that will work at all game levels, from design to game play to feed-back. IGER starts from the observation that commercial games are indeed too hard for most rehabilitation patients and specific games for rehabilitation are required. The introduction of a rehabilitation engine would make developing games easier: it would free the developer from having to start from scratch in designing games, providing all the basis functionalities required. Moreover, the rehabilitation game engine can also be used to enforce a shared design intent and thus provide design guidelines for both games and exercises, thus making the process of creating efficacious exergames easier and, in the meantime, helping in guaranteeing their validity. The game engine can also, as in our case, suggest a shared theme in both visuals and narrative to promote cohesion between different exergames, provide a framework to insert motivational elements and ultimately increase the user's immersion in the game world. Game variety of scenarios, balanced scoring system, quantitative exercise evaluation, audio-visual feed-back aims at maximum patient's motivation.

A preliminary test of the collection of games has been carried out on seven elder people (75 ± 7 years old) to analyze usability and accessibility. All subjects reported a very good reaction to the exergames. The scenarios were attracting and engaging and the games always challenging. The mechanisms were clear and

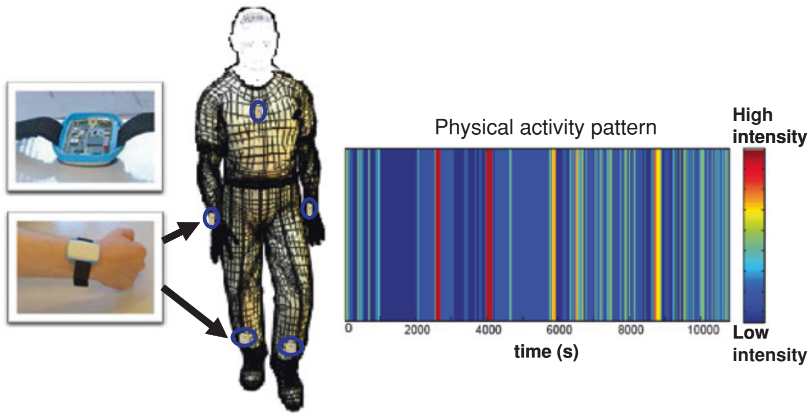

Fig. 16.12 Lifestyle physical activity assessment: the wearable devices and devised algorithms allow the long-term monitoring and assessment of daily-life activity pattern. The pattern may include multiple aspects of movement behavior (e.g. type, intensity, duration, etc.) allowing a comprehensive evaluation of daily functioning

could be understood in a little time: success or fail in any game action was clearly discernible. Monitoring was appreciated both by patients. The color feed-back was rated extremely clear as it appeared on the spot (the avatar) on which patients place their attention. This can be considered a better solution than for instance the scale and arrow used by Wii fitness that appears on the upper corner. Moreover, with monitoring patients were sure to perform the exercises correctly and they felt supervised although no therapist was present.

The physical/motor activity monitoring device (Fig. 16.12) is mounted with inertial (accelerometers, gyroscopes, magnetometers), environmental (barometric pressure, humidity, temperature) and ECG sensors as well as a radio and a micro-controller unit to provide the connectivity requirements. Inertial sensing is the key aspect in quantifying the type of activity and motion-related parameters. Environmental sensors are also important since weather-related factors may influence patients' behavior.

Two different interfaces can be used to connect the wearable devices with the external world depending of the amount of data to be transferred: a USB interface for large data transfer and a wireless transfer for smaller payloads. The device is also provided with a micro-SD card slot to allow for long-term recording of multiple modalities. The power autonomy is up to 20 h of continuous monitoring being able to record during the active part of the day and then get recharged overnight.

After recording the data is transferred to the computer for analysis. The analysis software provides a lifestyle physical activity assessment report which includes parameters quantifying the different aspects of physical/motor activity behavior. The information is synthesized and provided in various formats (tables, graphs or combination of both, Fig. 16.12) in order to allow a rapid evaluation by clinicians and to store it in the hospital database.

From these data the most appropriate model to seamlessly connect at home rehabilitation therapy to acute at hospital rehabilitation, appropriate service settings and adequate business models needed to guarantee a realistic implementation, adjusted to the needs of the patients and the reality and possibilities of service providers. Feedback obtained from REWIRE outcome will be crucial for the creation of best practices, guidelines and policy recommendations.

16.4 Conclusion

The structure described here allows integrating the aspects required for rehabilitation at home: the definition of a rehabilitation schedule combined with a review of the rehabilitation results gives to the rehabilitation treatment a full clinical value. Moreover, framing the progression of a patient inside the Gentile's taxonomy allows an objective choice of the exercises progression. The IGER game engine provides motivation, flexibility, adaptability and patient safety; it is therefore a good candidate to promote patients exercising at home, while supervising them to avoid maladaptation. Lifestyle evaluation through a body worn sensors network allows assessing how progression in the exercises transfer to everyday life. Lastly data mining functionalities allows the analysis of the big data provided by such platform.

Given all these characteristics, the REWIRE platform can be a good candidate to be successfully used to make rehabilitation at home possible and valid from the clinical point of view. This would represent a large step forward in rehabilitation, that could be taken out, at least partially, from the clinics and enable patients, discharged from the hospital, to continue their treatment intensively at home, where they feel most comfortable.

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Chapter 17
The Use of the Nintendo Wii in Motor Rehabilitation for Virtual Reality Interventions: A Literature Review

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Abstract Several review articles have been published on the use of Virtual Reality (VR) in motor rehabilitation. The majority of these focus on the effectiveness of VR on improving motor function using relatively expensive commercial tools and technologies including robotics, cybergloves, cybergrasps, joysticks, force sensors and motion capture systems. However, we present the case in this chapter that game sensors and VR technologies which can be customized and reconfigured, such as the Nintendo Wii, provide an alternative and affordable VR intervention for rehabilitation. While the performance of many of the Wii based interventions in motor rehabilitation are currently the focus of investigation by researchers, an extensive and holistic discussion on this subject does not yet exist. As such, the purpose of this chapter is to provide readers with an understanding of the advantages and limitations of the Nintendo Wii game sensor device (and its associated accessories) for motor rehabilitation

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and in addition, to outline the potential for incorporating these into clinical interventions for the benefit of patients and therapists.

17.1 Introduction

Recently, a number of studies have examined the use of virtual reality (VR) in motor rehabilitation [1]. These have employed a variety of VR technologies, such as robotics, cybergloves/cybergrasps, joysticks, force sensors and motion capture systems (e.g. IREX, PHANToM; SensAble Technologies Inc). The majority of studies have focused on the use of VR in the rehabilitation of neurological disorders [2, 3]; in particular, as an adjunct to promote upper limb recovery after stroke [4–6]. However, VR has also been utilized in the wider arena of rehabilitation including, rehabilitation of older people [7], balance [8, 9], burns [10], cardiovascular and general fitness [11], amputee rehabilitation [12], orthopedics [13], pediatrics [14] and intensive care [15].

Review papers concluded that while novel, VR and video game technologies could potentially be beneficial in rehabilitation and could be combined with conventional therapy [2–4]. However, only a limited number of studies included in the reviews, focused on commercial VR gaming systems, such as the Nintendo Wii [2, 3].

Use of gaming in rehabilitation is gaining in popularity and fits with current theories of motor recovery and motor learning which highlight the need for therapy to be motivational [16], intense and repetitive in order to maximize recovery [17]; The Nintendo Wii stands at the forefront of this development and is based around an intuitive motion sensor system that provides real-time information on performance, using visual, auditory and sensory feedback. However, the Nintendo Wii (as with other gaming sensor devices) has been designed for “fit and healthy” individuals, leading to concerns about its suitability for rehabilitation purposes. As a result, a number of researchers have evaluated the bespoking of such technologies [9, 18–21], yet to date, there are no literature reviews in this growing field of investigation.

This review has been conducted by a multidisciplinary team of computer engineers, designers and physiotherapists, with the purpose of:

- Defining the technical characteristics of the Nintendo Wii remote and balance board (Sect. 17.2), in order to facilitate the discussion of the technical merits and limitations of the technology.
- Reviewing the evidence for how the Nintendo Wii is being used and evaluated as a clinical adjunct to motor rehabilitation (Sect. 17.3 describing review methodology and Sect. 17.4 outlining the main findings)
- Detailing the advantages and limitations of the Nintendo Wii in motor rehabilitation, including any reports of adverse effects (Sects. 17.5.1 and 17.5.2)
- Highlighting potential uses of the Nintendo Wii in motor rehabilitation (Sect. 17.5.3)
- Identifying areas for future research (Sect. 17.5.3.1).

17.2 Technical Characteristics of the Nintendo Wii

17.2.1 The Nintendo Wii Remote (Wiimote)

The Wii Remote is a wireless low-cost controller for the Nintendo's Wii console that allows the user to interact with games and applications via gesture recognition. In electronics, the Wiimote is known as an inertial measurement unit (IMU) as it includes a combination of accelerometers and gyroscopes that measure velocity, orientation and gravitational forces.

Degrees of Freedom and Frame of Reference. The position of a rigid body has two components: linear and angular. A linear position displacement occurs at three perpendicular axes of the body's frame of reference (FoR) relative to another FoR, such as the earth's. Combined with angular displacement (rotation) on its own reference frame, this can provide the motion information of that body in three-dimensional (3D) space (Laviola et al. [22]). In other words, it can place the Wii remote in a 3D space environment. This motion is usually referred to as, forward/backward, up/down, left/right for the linear position and yaw, pitch and roll for the rotation. As the movement along each of the three axes is independent of each other and independent of the rotation about any of these axes, the motion is classified as having six degrees of freedom (6DoF) [23].

Connection with the Computer. The Wiimote typically communicates with a Nintendo Wii game console wirelessly via the Bluetooth interface. Equally, it can be paired with any device that supports the Bluetooth stack which implements the Bluetooth Human Interface Device (HID) protocol, such as a personal computer or laptop. Once the Wiimote is in a "discovery" mode (buttons '1' & '2' pressed simultaneously or the red sync button at the back) the operating system (OS) will recognize a HID-compliant device and a connection will be established. Considerable effort by the open source community has resulted in the ability to reverse engineer the structure definitions of the input stream, functions and signature calls. Various Wii-orientated, open source libraries have facilitated the interaction with a computer by using a set of common library functions:

- WiiYourself! [24]—A Windows OS based code, implemented in C/C++, fully-featured for most Wii's accessories (including Wii Motion Plus, Balance Board, Nunchuck and etc.) and supports all Bluetooth stacks.
- GlovePIE [25]—is a free Windows Programmable Input Emulator that uses scripts to interact with the computer. It is bounded on the functions provided by the emulator and no adaptation is possible since it is not distributed with the source code. Nevertheless, it is easy to use and provides an adequate support to most of the accessories.
- WiimoteLib [26]—A library for using a Nintendo Wii Remote from .NET. Recently updated for supporting Wii MotionPlus (the integrated version of the Wiimote and the Wii motion plus accessory). However, it was stated by the author as incomplete.

- Wiiuse [27]—A cross-platform C library that can be used with C/C++, Java and Python. It is light (in terms of the processing demands) and has a well-documented application programming interface (API). For Wii MotionPlus support, reference to other extensions from this library is required (e.g. libogc).
- CWiid [28]—A collection of Linux tools written in C for interfacing to the Nintendo Wiimote.

The choice of the library depends entirely on the system requirements and operating platform. The Wiimote includes an accelerometer and a gyroscope device, which are discussed below.

Accelerometer. The remote has the ability to sense acceleration along three axes via a three-axis linear integrated chipset.[1] Its main physical characteristic is that it can acquire measurements over a range of at least 3 g (gravity force) with 10 % sensitivity. Since the accelerometer actually measures the force wielded by a set of small proof masses inside the circuit with respect to its enclosure, it can only track liner gravity acceleration g (approximately $-9.8\ m/s^2$) in a free fall frame of reference and not horizontal rotation. Therefore, it can only be used to derive pitch and roll from the respective axes but not the yaw orientation [29]. Pure accelerometer-based solutions can only be deployed for applications with a fixed reference from gravity as well as linear or tilt movement, constrained to limited rotation.

Gyroscope. Gyroscopes can measure angular velocity which may be integrated over time to compute the sensor's orientation directly. Based on the principles of conservation of angular momentum, when the gyroscope device is rotated, the Coriolis force creates an orthogonal vibration force proportional to the rate of rotation. The Wii MotionPlus is the gyroscope component of the controller and comprises dual-axis and single-axis integrated gyroscope sensors. The first version of Wii MotionPlus featured an external peripheral attached at the bottom-end of Wii's remote controller.[2] As it features both dual-axis (for pitch and roll angular velocities) and single-axis (for yaw angular velocity), it has the capability to report full orientation tracking. Similarly with the accelerometer, the gyroscope's readings are in raw binary form (using a 14-bit ADC module) in order to get the actual angular velocity expressed in degrees per second.

17.2.2 The Nintendo Balance Board

The Wii Balance Board is a game controller that is predominantly used in combination with the Wii and its associated software. It uses standard Bluetooth technology to communicate with the Wii. In addition it can be connected to a personal

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[1] Analog Devices, Inc., "ADXL330 Data Sheet Rev A," September 2009. Available: http://www.analog.com/static/imported-files/data_sheets/ADXL330.pdf [6 November 2013].

[2] InvenSense Inc., "World's Leading Multi-axis MEMS Rate Gyroscope Enhances Performance of Latest Wii MotionPlus Accessory" May 2010. Available: http://invensense.com/mems/gyro/documents/articles/071508.html [6 November 2013].

computer using any of the aforementioned open source software applications. The balance board allows players to control games simply by shifting their weight. This is achieved by four pressure sensors situated at each corner of the board (with 43 cm between left and right sensors and 21 cm between top and bottom sensors) allowing the detection of slight movements and determining foot position and weight distribution. Each sensor can assume a weight value, which is equivalent to 34 kg.

17.3 Review of Literature

17.3.1 Search Methodology

The search strategy was developed in stages. An initial text search of ACM (Association for Computing Machinery) and IEEE (Institute of Electrical and Electronics Engineers) was carried out using the terms “Nintendo Wii AND motor rehabilitation OR Neurorehabilitation” to find exemplar articles from which to harvest indexing terms. The bibliographic details for each item from the initial search were reviewed independently by members of the project team (ET and DS).

Following this, the categories and keywords were fine-tuned to ensure all exemplar articles were returned in the final database search. An extensive literature search was conducted using the seven electronic research databases most frequently used in the fields of technology, computer science, engineering and medicine: the IEEE Explore, ACM, Science Direct, Web of Science, Scopus, MEDLINE and PubMed.

The search was performed in January 2012 using the following keywords: Nintendo Wii, Wii remote, Wiimote, Wii balance board, Nintendo balance board, Wii fit, rehabilitation, motor rehabilitation, neurorehabilitation, stroke. These keywords were combined using the Boolean operator AND or OR with the aforementioned keywords to create the following three groups of search terms:

(Nintendo Wii OR Wii remote OR Wiimote OR Wii balance board OR Nintendo balance board OR Wii fit) AND (rehabilitation OR motor rehabilitation OR neurorehabilitation OR stroke)

Search terms were entered in each selected database, providing a unique search outcome per database (see Fig. 17.1).

Article titles and abstracts were read (by ET and DS) and those that matched the review questions, inclusion/exclusion criteria and keywords were retrieved. In the case that the title and abstract did not contain enough information to decide on inclusion, the full article was read. Further screening of the full papers was performed by the review team (ET, DS, CK, IP, AW). Papers retained for the final review were based on the original review questions as well as a second set of inclusion/exclusion criteria (see Fig.17.1). All papers were screened by two

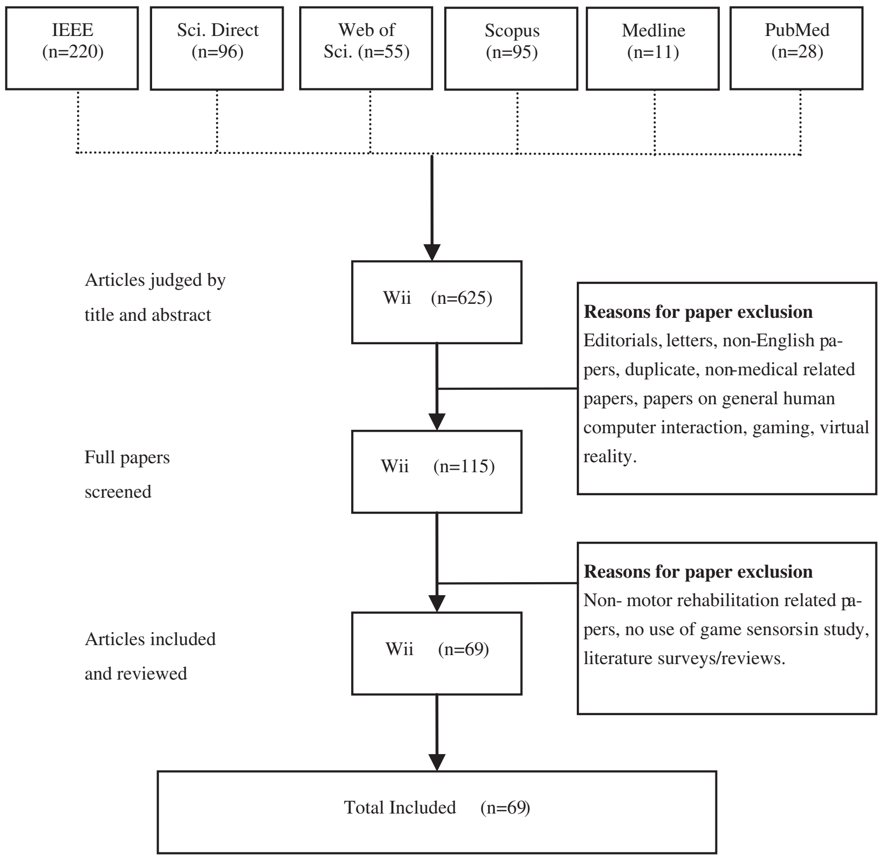

Fig. 17.1 Search strategy

reviewers independently. Discrepancies were resolved by consensus or involvement of a third reviewer.

Inclusion and Exclusion Criteria: Inclusion and exclusion criteria were used to refine the search results. Firstly the search was limited to English text papers published in peer-reviewed journals and conference proceedings from January 2006 (when the Nintendo Wii was released) to January 2012. Secondly, editorials, letters, book reviews and book chapters were excluded, as were papers unrelated to motor rehabilitation and those that did not employ the use of game console sensor devices. In addition, articles which related solely to the use of the game console sensor devices for the purposes of human computer interaction (HCI), gaming and VR in general, were excluded from the study. Literature review papers were not included in the final critical appraisal but were drawn upon for cross-validation of our findings.

Figure 17.1 shows 625 original articles and reviews were identified. Inclusion and exclusion criteria (as outlined above) were applied to the abstracts resulting in the removal of 510 articles. The remaining 115 full text articles were scrutinized and a further 46 were excluded at this stage, resulting in the inclusion of 69 original articles for this review.

17.4 Summary Findings

Study characteristics are presented in (see externally linked file: [30]). All chapters discussed the efficacy and/or development of the Nintendo Wii for motor rehabilitation. These can be divided into five key areas, namely:

- game sensor device type (i.e. the Nintendo Wii remote and/or balance board);
- level of sensor device customization (i.e. whether the console was original or customized (bespoke) for the purposes of the specific intervention);
- type of intervention (i.e. whether a console game was used, custom made game or custom made exercise was developed);
- study characteristics (i.e. specific characteristics of the intervention such as the study design, duration, participant population and outcome measures used) and finally;
- the study results (i.e. intervention effect and whether any adverse events had occurred).

Game Sensor Device Type. Sixty-nine studies employed the Nintendo Wii remote sensor and/or balance board as a tool for motor rehabilitation. The remote sensor device was more widely employed, being specifically used in 38 studies (55.1 %) compared to 25 (36.2 %) which only used the balance board and 6 (8.7 %) which included both devices. The reason behind this can be sought in the specific health specialties where each sensor has been used. For example the Wii remote has been employed by 20 studies developing interventions for upper-limb stroke rehabilitation and other upper limb motor rehabilitation pathologies, such as orthopedics, amputee rehabilitation, cerebral palsy. The balance board, on the other hand, has been utilized mainly for balance specific disorders.

Level of Device Customization. Closer scrutiny of the Nintendo Wii game sensor studies revealed that overall 36 studies[3] (52 %) employed customized versions of either the Wii remote or balance board. Customization of the Wii game sensors suggests that instead of using the commercially available Nintendo Wii console for rehabilitation, the authors used bespoke versions where the Wii game sensors were connected to a personal computer (PC). It is interesting to note that game sensor bespoking occurred in 67 % of studies that employed the Wii remote sensor (30 out of 45 studies) of which 50 % were in neurological conditions, whereas only 32 % of studies (10 out of 31) bespoke the balance board. This indicates that for the purposes of motor rehabilitation, the Wii remote requires

[3] Two of the 36 studies employed customization for both the Wii remote and balance board.

customization more often than the balance board in particular for use by neurological patients.

Type of Intervention. Despite the tendency for game sensor customization, there was a balance between the use of standard commercially available console games and the development of custom games and exercises. Thirty-five studies used existing games played on the corresponding game console and 34 utilized either custom developed games (13 studies) or custom developed exercises (21 studies) to help deliver motor rehabilitation.

With regard to the customization of the intervention, two distinct groups were apparent: those which developed customized exercises and those which developed customized games. In the former, the patient accomplished tasks in the context of a game, whereas in the latter, the patient was directly guided throughout the movement. Typically VR environments for upper limb rehabilitation were categorized as game-like or teacher-animation [31].

Customized exercises were typically therapist-designed and required repetition of desired movements, whereas the customized games involved game design concepts and game mechanics for conducting rehabilitation exercises in a more motivating and implicit manner [9, 15, 32–42]. Moreover, both were designed to be used on a PC instead of the original game console device.

Study Characteristics. The Wii was used across a variety of clinical specialties such as neurology (including stroke), rehabilitation of older people, respiratory, burns, pediatrics, intensive care, amputees, falls & balance and orthopedics, suggesting that the Wii may potentially be a useful adjunct in the rehabilitation of a wide variety of conditions. Stroke was the most commonly explored condition (43 %—30 studies), followed by balance disorders (22 %—15 studies) and then other motor rehabilitation (12 %—8 studies). In studies that only used the Wii balance board sensor, 58 % (18 of 31 studies) explored balance in general and 42 % (13 out of 31 studies) looked at balance specifically in stroke.

The review revealed that the Wii is being used as an assessment device and for treatment. Of the studies reviewed, 9 (13 %) were concerned with using the Wii as an assessment tool and 60 (87 %) were concerned with using the Wii as a treatment. Overall, 34 (49 %) looked at the efficacy of using the Wii as a treatment, 30 (43 %) were more focused on development of Wii as a treatment (including feasibility, acceptability and technical details regarding customization) and 5 (7 %) looked at both aspects).

Methodological issues limit the conclusions that can be drawn as the majority of studies (n = 31, 45 %) were pilot or quasi-experimental (utilizing either pre-post designs, or pilot studies, or single case experimental design, or controlled trials without randomization). Only 9 (13 %) were randomized controlled trials (RCT). Five studies (7 %) were observational. A further 5 were case studies (7 %) and 4 involved qualitative methodologies (6 %). Many devices appeared to be untested (n = 16, 23 %) whereas others were tested but on a non-target group (e.g. a device designed for use in neurology was tested on people who were neurologically intact). In addition, the majority of studies were underpowered with small sample sizes.

Furthermore there was a lack of information regarding the duration of the study in 22 (32 %) of the 69 studies. Where stated, the most common study duration was 2 weeks (n = 20, 29 %). Three studies lasted for 5 weeks, 2 for 12 weeks and 2 for over 3 months. In terms of the duration of the intervention, 31 (45 %)) lasted for one hour, 14 (20 %) lasted for 20 min, 14 (20 %) lasted for 30 min, 7 (10 %) lasted 10 min and 4 (5 %) lasted for 15 min. Interestingly only four studies involving stroke [9, 16, 43, 44] achieved the UK recommended minimal intensity of 45 min a day and not all of these managed to deliver the intervention for the recommended five days [45].

As can be seen from the externally linked Table [30] a variety of outcome measures were employed. These included measures of impairment of body structure and function (such as the Modified Ashworth Scale and Fugl-Meyer Assessment), measures of activities (such as the Berg Balance Test, 10 m Timed Walk) and measures of participation (such as the Stroke Impact Scale). Few studies employed measures looking at all three levels. In addition, a number of studies employed outcomes, which were not validated or tested for reliability and others suffered from the use of measures which were not sufficiently sensitive to detect clinical change and this may have affected the results obtained.

Study Results. There is increasing evidence in support of the use of the Wii for rehabilitation in a number of different clinical areas including the upper limb following stroke [16, 44, 46, 47], balance [8, 9, 48, 49], post total knee replacement [13] and fitness [33, 50, 51]. However, the evidence is not conclusive and more robust studies are required (incorporating changes suggested in the next sections of this chapter) before the technology can be integrated into rehabilitation outside of the research setting.

Relatively few adverse effects were noted suggesting that the Wii is a safe to use with subjects with motor problems. When reported, adverse effects were minor in nature, such as mild shoulder pain (reported by 2 out of 10 stroke patients following 30 min of intense exercise) [50], knee pain (one person with multiple sclerosis) [52], slight loss of balance stepping off the balance board and one episode of light-headedness on exercising with the Wii [53]. Interestingly, no falls were reported in any study and no adverse effects (including cardiovascular issues or accidental removal of artifacts i.e. intravenous lines) were reported when using the Wii with 22 subjects in an intensive care setting [15].

17.5 Advantages and Limitations of the Nintendo Wii in Rehabilitation

This section brings together findings from the literature review related to the key advantages and limitations of the using the Nintendo Wii in motor rehabilitation from both the technical and clinical perspective.

17.5.1 Technical Advantages and Limitations

A number of technical advantages and limitations have been highlighted from the literature.

The Nintendo Wii is a relatively affordable gaming console (around £180[4]) with the accessories of the balance board and Wii remote also available at comparatively accessible costs of around £80 and £35 respectively. It is a relatively affordable piece of equipment that is commonly found in many homes and therefore. specific exercises (from the Wii sports and fitness game series) and game challenges can be given to people to perform at home as part of their home rehabilitation program.

As the Nintendo Wii accessories can be purchased individually, they can be used with a personal computer (using the available open source software applications presented in Sect. 17.2) to create customized applications. The open source software applications, although free to use, require considerable technical knowledge to be employed. However, they allow up to four Wii remotes to be simultaneously connected to a computer at a given time. It is therefore possible to create games or exercise routines where the Wii remotes can be strapped (using arm/leg bands) to the arms or legs of the user to drive the games or rehabilitation exercises. Bluetooth compatibility issues with different types of stack and various versions of the Wiimote, means that at times, the process of pairing a Wii remote with the computer has to be done manually, something most users can be easily trained to do. An alternative is to use commercially available Bluetooth pairing software such as the BlueSoleil Software.[5]

As can be seen in the summary findings section (Sect. 17.4), half of the studies examined have opted for customizing the Wii. The main reasons for this are as follows:

- Accessories such as the Wii remote and balance board provide cheap IMU and balance training equipment when compared to similar commercially available therapy solutions, such as high-cost force plate systems or optical motion capture systems [20, 54–57].
- The data generated from the commercially available Wii remote and balance board when used with the Nintendo Wii console cannot be extracted for analysis by the therapist. For instance, valuable information such as the amount of acceleration, the degree and range of movement can only be accessed via pairing the Wii remote or balance board with a computer using the open source software available.
- The unsuitability of many of the commercially available game packages limits their potential use to just a few health conditions, such as musculoskeletal. Games ideally should be able to be customized and personalized for the

[4] See Amazon UK at www.amazon.co.uk, prices in June 2013.

[5] BlueSoleil Software. Available at: http://www.bluesoleil.com/index.aspx [6 November 2013].

individual and their health condition in terms of the level of difficulty, the speed of gameplay, the range of motion, and types of exercises.

- Although the interaction paradigm of engaging with the games through physical interaction is generally regarded as intuitive, issues are apparent when using commercial games and exercises for the purpose of motor rehabilitation [38]. For example, feedback has been identified as inappropriate and often discouraging by users with motor disabilities [49, 56, 58, 59] and scoring systems have been found inadequate as a measure of performance and progress [19, 59, 60]. Furthermore, the amount of time to set up the equipment has been identified as an issue for therapists with Annema et al. [32] noting this frequently took up half of the treatment time and Mouawad and Doust [44] observing that stroke patients frequently required over ten minutes to activate games compared to less than one minute for the neurologically intact .
- Monitoring of patient performance is an essential element for therapists, who unless physically present cannot evaluate and monitor patient performance and adherence to exercise [3, 61–63]. Logging of data and patient performance is only possible through employing a customized Wii solution.
- The accuracy of motion and balance data, results in the capture of more robust and clinically important data, such as range of movement across three or more DoF.

For data accuracy, it should be noted that although the Wiimote includes both an accelerometer and a gyroscope, acquiring an accurate 3 DoF movement known as pitch, roll and yaw from the device itself is very challenging. For this reason the Nintendo Wii console comes with an LED sensor bar that the infrared sensor positioned at the front of the Wii remote employs to detect the yaw movement of the remote. However this only works provided the two devices are in line of sight (facing each other directly over a specific distance). This limits the type of exercises and range of movement that can be achieved. For instance exercises which require a large range of motion (such as a basic shoulder flexion-extension movement) cannot be captured by the Wii remotes [18].

In addition to this, as electromechanical devices, both the accelerometer and gyroscope, are prone to noise, errors and bias [57]. This can be minimized, thereby improving the accuracy of the Wiimote, by filtering these out. However, it is important to avoid degradation of the raw output data while doing this. There are various methods to filter out the noise, some involve complex computations but offer impressive results and others have few computational methods but use data that is initially very distorted [64]. The choice of selecting the right tradeoff depends on the characteristics of the signal (peak position, height, width, area, etc.) and system requirements. It should be noted that in most algorithms, the intervals between adjacent data points or within a window frame must be obtained at the same time. Both the Wiimote's accelerometer and gyroscope have a sampling rate of 100 Hz but in reality there is a uniform distributed delay of 1–5 ms, which is considered to be a negligible part of the computer's processing cycle.

Additional issues can be found with the data produced by the gyroscope, which calculates the yaw range of motion. After significant rotation the yaw orientation will be misaligned, also known as "drift", because IMUs suffer from accumulated error; they continually add detected changes to their previously-calculated positions and any errors in measurement, however small, are accumulated from point to point. Thus, the yaw position has to be reset to a known point (e.g. zero as the pointing forwards) otherwise the yaw rotation given will be inaccurate.

Several studies have developed customized Wii-based interventions aimed at developing a VR-based system that captures the patient's arm motion in a more accurate way compared to the conventional Wii remote. These can be categorized into three main groups depending on the technical methodology employed for customizing the Wii remote: acceleration data only, Wiimote and light-emitting diodes (LEDs) as an infra-red (IR) camera and a hybrid of the two.

The majority of customized Wii remote stroke interventions employ one or two Wiimotes with a reverse engineered (API) to capture the patient motion by reading the Wiimote accelerometer data.

A number of algorithms have been suggested and implemented by various research groups to filter data and map them to motion, in order to drive either a set of exercises or custom-built games (such as [18, 21, 65, 66]). Since all these approaches obtain the position of the Wiimote in space using the acceleration data (that is the change in the linear acceleration as the patient moves the Wii remote in space) they suffer from a DoF limitation. More precisely, these solutions offer accuracy only in 2-DoF as the acceleration data can only determine the pitch and roll movement. Such systems are therefore more appropriate for gesture-based interventions rather than one-to-one mapping (kinematic animation) of movement onto the VR environment.

Another common Wiimote customization involves using a pair of Wiimotes with the LED sensor bar or custom LEDs to act as an IR camera to create a low-cost motion capture system [20, 57, 62, 67–69]. Reflective markers or LEDs are usually placed on patient's arm or hand and as the exercises are executed, the range of motion is captured and mapped onto the system display. The limitation in this approach is that each Wiimote can only detect up to four LEDs in space, thus restricting the range of movement and set of exercises that the patient can do. Care must also be taken to ensure the angle of the Wiimotes does not obstruct the LEDs as the patient moves his/her arm. Moreover, the use of LEDs often requires extra power supply devices to be attached to patients. Wilson [69] and Martin-Moreno [62] have proposed a hybrid solution that incorporates the two aforementioned approaches in an effort to increase accuracy and the number of DoFs. However, this approach also suffers from a limited field of view by employing the Wiimote as an IR camera making it unsuitable for tracking larger motions often required in therapy [18, 36].

Although not designed specifically for motor rehabilitation, Williamson et al. [70] have proposed a Wii-based system that merges acceleration with gyroscope data and the Wiimote's IR. This system is aimed at motion recognition for sport-like games (e.g. American football) and not for kinematic analysis and mapping of user motion onto a 3D avatar (virtual character) but could potentially be adapted for motor rehabilitation. Their developed data fusion algorithm requires the use of the Wiimote's IR to compensate for the gyroscope drift and movement corrections. Results indicate improved motion recognition when compared to acceleration data alone but still show loss of accuracy when the IR is out of sight.

There are other technical solutions that could resolve the yaw orientation drift issue and hence provide a fully accurate 3 DoF Wii remote system without the need to use the LED sensor bar that comes with the Nintendo Wii console. One solution is to integrate a magnetometer device. Magnetometers are electromechanical devices, that measure the strength of direction of the earth's magnetic fields and can be used as a reference point for correcting the gyroscope's yaw drift.

Another workable approach to the problem is to process concurrently and conjointly both sensors' (accelerometer and gyroscope) measurements through a data fusion algorithm [71]. There are a number of different fusion algorithms that can be employed, such as the discrete-time complementary Kalman filter [72], the Newton-Raphson optimization method [73] and several others. The decision on which to use is a trade-off between the computational power available and the accuracy level required for the Wii system. For instance, higher accuracy levels can be achieved using the Kalman filter but a powerful computer will be required to process the data fusion algorithm and the data in real-time.

Raw information captured from one sensor can be used to distinguish true readings of the other, and vice versa. In addition, the angular rate measurements captured by the gyroscope sensor can be used to distinguish true linear motion from the accelerometer readings. When used in combination with a matching human body's kinematic analysis, a highly accurate, highly responsive, one-to-one representation of the control device in 3D space (with 3 DoF) can be achieved.

An additional advantage of the Wii remote, currently underutilized by the research community, is the possibility for providing the patient with haptic feedback via its rumble feature [62, 74].

Compared to the Wii remote, the balance board is easier to customize and incorporate from a technical point of view, although knowledge of how to use the open source software applications presented in Sect. 17.2 is still required. By knowing the location and distance of the four sensors, a number of different algorithms can be used, to calculate with accuracy the weight transfer and position of the person on the board [9, 75, 76]. For instance, different movements such as a jump, press up or knee bend can be identified, displayed graphically on a 3D character on the computer screen and recorded for later monitoring by the therapist. These movements can either be incorporated into a game or given to patients as exercises to follow. A key advantage of the balance board is that it can be used as an affordable alternative to more expensive force platforms [48, 54, 75]. As with the Wii remote, patients using the balance board do not explicitly associate the exercises with rehabilitation but with gaming and fun [9]. In addition, the Wii Fit game, and newer customized video games that are geared more towards balance training can be created for use with the computer [9, 19, 77].

There has been extensive discussion in the literature regarding the benefits of virtual reality (VR) in rehabilitation ([2, 3, 16]; Ke et al. 2011). VR refers to a computer-based technology that provides users with computer graphic generated simulated worlds and environments where users can interact and explore whilst receiving multisensory feedback (audio, video, tactile). VR applications can be immersive or non-immersive depending on the degree of immersion into the computer world and the technology employed. In the former, the user interacts with the simulated environment through head-mounted displays and other specialized and often expensive devices; whereas in the latter the user is not fully immersed in the environment and cheaper alternative physical sensors are employed. Gaming technologies such as that of the Nintendo Wii are considered as non-immersive VR applications. Such applications allow the user to receive immediate feedback of his/her physical actions and movements on the computer screen (registered through the Nintendo Wii and other similar technologies). This is usually presented to the user in the form of either a third person (i.e. seeing a virtual character mirroring his/her movements) or a first person view (i.e. seeing the environment, through the eyes of the virtual character). An additional challenge to consider when using customized games with the Wii remote controller for the purposes of rehabilitation, is that of calibration [18, 32, 36, 47]. Calibration refers to manually, or preferably automatically, adjusting the game to the patient's morphology by measuring the abilities of the player, such as the speed, reaction time and range of movement [36].

17.5.2 Clinical Advantages and Limitations

As a commercially available, off-the-shelf gaming solution, which is common in many households [8, 19, 40, 50, 58, 78], the Nintendo Wii represents a piece of technology, which is familiar to many users of differing ages [79]. In addition it is relatively inexpensive, is well received by therapists and patients alike [10, 60] and is perceived as a "normal activity" that is not associated with medical treatment or disability [74]. This may potentially lead to a greater acceptance and willingness to use the technology as part of the rehabilitation process [9, 10, 32, 35, 49, 60, 80].

The fact that Wii and other gaming systems are considered as safe and enjoyable suggests that patients are more likely to engage in these activities for prolonged periods of time. It has therefore been postulated that use of such systems in rehabilitation has the potential to deliver the intensity and repetition of activity necessary to drive motor recovery [16]. This would be particularly advantageous for home based rehabilitation where lack of adherence to home exercise programs has been a notable issue [81].

Being primarily a game technology, users can select from a plethora of games and this variety is likely to reduce boredom and further encourage use. However, as they have been targeted for the fitness and leisure industry, not all games are suitable for motor rehabilitation. In fact only a few titles (such as the Wii Sport, Wii fitness) include activities that are appropriate for physical rehabilitation.

The literature [33] and specialist web blogs [82] have complied a list of titles and corresponding exercises which may be beneficial for use in rehabilitation.

While the evidence suggests that off the shelf systems appear to be effective at addressing issues of balance and fitness [8, 9, 42, 49, 51], there is less evidence in support of the use of the off the shelf Wii for upper limb rehabilitation following stroke, indeed many studies indicate the need for customization for this patient group [44, 60]. Due to problems of reduced range of movement, dexterity, speed and strength that characterize physical abilities post stroke, stroke survivors with upper limb problems are likely to have difficulty in holding and operating the Wii remote and in engaging with off the shelf games [18, 44, 47]. It is therefore probable that upper limb rehabilitation following stroke will require customization of games and some form of strapping to attach the Wii remotes to the arm. It should be noted that even amongst patients with the same pathology, a wide range of impairment can be seen and therefore systems will need the ability to be individually calibrated with regard to range of movement, type of exercise, difficulty, and speed.

In addition to providing a motivating and individually calibrated way of rehabilitating patients, as previously described, the ability to bespoke the game sensors means data can be captured and accessed by the therapist and patient for evaluation and monitoring. Nonetheless, while the evidence base for using the Wii in rehabilitation is developing, it remains inconclusive. In part this is due to a lack of studies investigating the efficacy of the device [with 30 studies (43.5 %) reporting on technical developments alone] but this is also due to methodological weaknesses of many studies, with poor description resulting in difficulty ascertaining the legitimacy of findings and relevance to the clinical situation. Issues of spontaneous recovery (which is possible for up to 6 months following stroke) and practice effects (when improvement in performance is due to repeated exposure to the outcome measure and not the intervention) may have provided false positive results. In addition, some studies used inappropriate outcome measures, often lacking sensitivity to detect change, thus reducing the likelihood of clinically meaningful results and up take by therapists into practice.

17.5.3 Potential of Using the Nintendo Wii in Rehabilitation

The literature identifies several advantages, limitations and potential uses for the Nintendo Wii as part of rehabilitation. These are outlined in Table 17.1.

Around 15 million people in England have one or more long-term conditions [83], a number which is predicted to rise by a third over the next ten years [83] This, combined with changes in delivery of healthcare (with a greater focus on community care and less hospital based treatment), means that the demand for therapy is set to increase. Conversely, the numbers of therapists being trained is falling in the UK [84] and there is an acknowledged lack of therapists to supervise exercise in community settings [85]). This dichotomy has highlighted the need

Table 17.1 Advantages, limitations and potential of the Nintendo Wii

Advantages	Limitations	Potential
Suitable in its current form for use in rehabilitation of some health conditions	Not suitable for all health conditions Need for calibration for use with patients with differing conditions and levels of impairment	Personalized games can be designed for specific needs of patients
Relatively low-cost. Accessories can be purchased on their own	Need to customize to use accessories on their own	
Variety of activities and games	Unclear which games are suitable for patient use	Library of games needed linked to conditions
High market penetration into households		
	Some patients cannot hold the Wiimote	Can employ armbands to strap Wiimote to upper/lower limbs
Not associated with medical interventions	Game feedback is not patient-friendly	Can be incorporated into personalized activities. Patient useful feedback can be created
Open source libraries to support connectivity with a personal computer	Technical knowledge is required	Partnership opportunities for engineers and therapists to work together
Enjoyable (effect on motivation and adherence)	No way of monitoring patient progress and adherence to rehabilitation regime	Networking capabilities enabling telerehabilitation and monitoring
Few adverse effects	Slow set up	
Gamification of motor rehabilitation (patient motivation)	A few titles suitable for patient use only	New games customized to suit the individual needs of the patient can be created
Bluetooth interface allows connectivity with computers	Bluetooth compatibility issues with different versions of stack and various versions of Wiimote	
Filtering algorithms can be used	High level of noise introduced by the sensors' sensitivity	
Data fusion algorithm provides a solution to the bias drift problem	Data fusion algorithm requires the use of IR sensors to recalibrate yaw over time in order to compensate the bias drift	Accurate 3 DoF (pitch, roll and yaw) can be achieved
	Evidence base for use in rehabilitation inconclusive	More research of higher experimental rigor is required

for patients to be more involved in their care and in particular, being motivated to exercise independently. However, compliance with therapy is notoriously poor [86, 87], with a recent study highlighting that within two days of discharge only 79 % of patients were continuing with their home exercise program as prescribed

[81]. Reasons for lack of compliance are complex and beyond the scope of this chapter, however there is evidence that boredom with traditional exercise and a lack of monitoring by therapists are contributing factors [88, 89].

Gaming is well received by patients and therapists [49, 60, 80] and is embedded into society where it is played by people of all ages [79]. This suggests that the use of VR exercise devices, either as part of a home exercise program or when combined with telerehabilitation, with monitoring abilities, has the potential to help address the important issues of motivation and compliance. This is a particular issue in stroke rehabilitation where greatest recovery is associated with high frequency, high intensity repetitious practice [17] involving a recommended minimum of 45 min daily for 5 days a week [45]. Moreover, teletherapy could potentially reduce the need for resource-intensive home and hospital visits and save travel costs [90].

A number of review papers have examined the benefits of virtual reality based systems in stroke and motor rehabilitation in general. However the majority of these, focus on expensive and VR dedicated hardware devices, such as head mounted displays, cyber-gloves, cyber-grasps and haptic devices (i.e. Phantom device, joysticks and force sensors) [3]. Although a few studies have investigated the development and use of VR-based interventions and telerehabilitation, all employ one of the aforementioned expensive hardware devices [56, 91]. Only one paper has proposed a Wii-based system offering a telemonitoring facility but this is based on using Nintendo's own network and platform, which is not suitable for holding private and secure patient records [61]. Therefore there is a challenge as well as an opportunity here. The Nintendo Wii could, if customized, presents a way to enhance community based stroke rehabilitation of the upper limb by providing a motivating and cost-effective way of exercising that can be remotely monitored and exercises adjusted as required by a physiotherapist.

For this to be implemented a number of key requirements must be fulfilled. The motion capture information (received from the Wii Remote and/or balance board) should be stored on a database, which can maintain the recorded sessions for each individual patient and be available to the therapist for evaluation and monitoring. This would serve as a direct link between the patient and therapist, therefore it could also be used as a communication tool (e.g. the therapist could leave messages for the patient to receive or amend the patient's exercises as s/he progresses). As the server relays sensitive information, a set of secure protocols would be necessary to avoid malicious interception from external sources. The use of network sockets would be beneficial for the communication of data between the patient and therapist, as it enables interoperability of the data usage in a cross platform environment (bidirectional inter-process communication flow across the host computer and a remote network) and the ability for the therapist to monitor patient progress both off-line (store-and-forward method) but also in real-time (getting a real-time 3D visualization of the patient's current exercise activities).

Therefore the use of the Nintendo Wii could present a potential solution to community based rehabilitation by providing a novel, motivating way of exercising either as a stand-alone solution or with the addition of teletherapy when it could be remotely monitored and adjusted as required by a physiotherapist.

In addition, Wii-based telerehabilitation interventions support games that potentially can foster cooperation and competition amongst community users. Cooperation through gameplay has the potential to increase levels of patient motivation as they could on one hand feel part of a wider community (of people with a similar condition) where personal experiences and stories could be shared and peer-support facilitated; and on the other, competition would provide an additional incentive for continuing with exercising. Here the research community can make a significant contribution in the form of creating a secure and private online social network, specific to local communities, offering patients with relevant/similar health conditions the opportunity to be socially integrated with the community from their homes.

17.5.3.1 Recommendations for Future Studies

A number of recommendations can be made based on the discussion of the literature.

Technological Recommendations. In addition to the development and testing of teletherapy and activities that can be customized and adapted to individual patient needs (as outlined above), future developments should ensure that systems are quick and easy to set up and that frequent feedback which is accurate and motivating is provided [18]. Moreover, new systems should be able to record progress and in addition, they need to be affordable.

Need for Motor Rehabilitation Specific Game Design Guidelines. The customization of a game for rehabilitation purposes is a complex procedure that requires a different approach than traditional game design. The literature suggests that relevant studies utilizing customized games do not always present a specific game design framework or at least some recommendations or guidelines on this matter [18, 32]. Hence it is recommended that a clear game design framework and game design guidelines specific to customized games for motor rehabilitation forms a focus area for future research studies and their accompanied publications.

Research Collaboration. A closer look at the literature presents a picture where most studies have been conducted in isolation with none or little communication between researchers. Each research team uses different commercial games and exercises with different intensity levels. Although a number of customized games and exercise packages have been developed by research teams for the purposes of rehabilitation, most remain inaccessible to the rest of the research and therapy community. Therefore there is a need for the research and therapy communities to work together to produce an online pool where all pilot tested, personalized, adaptable games and exercise packages developed by research teams, are made available with instructions for the wider community to use in practice. This will help in disseminating best practice in the use of such interventions in rehabilitation and in addition, will assist the research community in testing these interventions on a larger scale and therefore will produce more robust outcomes.

Study Methodology. The issue of experimental rigor is fundamental for helping to promote the uptake of a new therapy into clinical practice, as the drive for evidence based therapy is fundamental. Therefore before a technique can be adopted into clinical practice, it must first be evaluated for efficacy [92] and in addition, it must be evaluated for feasibility and acceptability. In light of this it is imperative that the methodological issues, which characterize much of the literature, are addressed. Study designs need to take into account the potential for spontaneous recovery and practice effects and allow prolonged baseline measures or the use of control groups to account for this. In addition, publications need to more fully describe their methodologies and patient characteristics in order to allow therapists to ascertain the relevance of the study to their patient group. This requires the testing of equipment on the target group involving subjects with the condition under investigation. Furthermore, future studies should consider use of outcome measures which are reliable, validated and sensitive to change. These should address different domains of disability including impairment and functional measures as well as measures of quality of life.

Compliance. As compliance with an exercise program is key to its success, future studies should examine whether the use of Wii and gaming technology improves compliance with treatment.

Finally, to ensure technical developments are clinically useful and acceptable, the reviewers of this paper strongly recommend engineers, therapists and patients work in collaboration, thereby addressing issues of patient and therapist requirements, issues regarding acceptability and feasibility and an understanding of what is possible technically.

17.6 Conclusion

Through systematic reviewing of the literature, this chapter has outlined the advantages, limitations and the potential uses of the Nintendo Wii as an adjunct in motor rehabilitation. While the Nintendo Wii is not the only commercially available gaming technology where user movement can be tracked, the rationale behind the use and presentation of the Nintendo Wii, arguably lies in its popularity in the home, research and clinical communities. The comparison between the various gaming devices (such as the Sony Move controller and Microsoft Kinect) is out of the scope of this chapter. However several of the benefits, limitations and potentials presented through this paper are applicable to these gaming devices.

The growth of VR systems, in particular interactive gaming has accelerated in the last few years, and the Nintendo Wii stands at the forefront of this development. This chapter has highlighted the potential of gaming technology within health and social care settings and the importance of collaborative working between engineers, therapists and users of technology. In light of the projected growth in people living with long term health conditions and the resultant effect on health and social care resources, the need for evidence based, innovations which promote self-management are required to meet these challenges.

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Chapter 18
A State of the Art Survey in the Use of Video Games for Upper Limb Stroke Rehabilitation

Owen O'Neil, Christos Gatzidis and Ian Swain

Abstract Recent developments in approaches to stroke rehabilitation include the use of video games as a mechanism to enhance motivation and compliance to upper limb motor practice. The fields of robotics and virtual reality use gaming simulations in order to promote high volumes of task specific movements that are capable of facilitating functional recovery. In this chapter we present a state of the art survey on the design, issues, clinical impact, and finally range of technologies that use video games as part of targeted interventions for the upper limb.

18.1 Introduction

Stroke is today the most prevalent form of severe adult disability in Europe and a major consumer of health care resources [30]. In the UK incidence rates suggest that, annually, over 150,000 people suffer a first time stroke [119]. For these individuals, acquired cognitive and motor impairments are common, occurring as a consequence of localized damage to areas of brain tissue [25]. Treatment is delivered via resource intensive one-to-one sessions from speech and language, occupational, and physiotherapists [29, 42, 65].

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For the upper limb, rehabilitation aims to ameliorate deficits in fine and gross motor control, with a focus on relearning functional movements important for activities of daily living [94]. Effective recovery is dependent on high volumes of motor practice, inducing neural plasticity, a form of cortical "re-wiring", allowing the central nervous system to respond and adapt to damage in motor networks sustained from stroke [39]. Managing access to this level of therapy on a one-to-one basis is both difficult and expensive. For example, in the UK evidence suggests that only 42 % of physiotherapy, 16 % of speech and language and 84 % of occupational therapy services meet stroke strategy staffing guidelines [75]. The consequences of both the demand on, and scarcity of, resources means that delivering enough therapy for optimal recovery can be costly and logistically difficult [83]. At present, one-to-one treatment is often bolstered by take-home exercises targeted at achieving higher levels of motor practice; however due to a range of psychological and physical factors, compliance to post-stroke home exercise is often not adhered to [54, 108].

In response to this problem, there is an impetus on research to investigate interventions that may present cost-effective solutions to increase a patient's access and compliance in motor therapy. Recently, virtual reality and robotically-assisted approaches have shown promise by integrating gaming activities as a mechanism to provide a semi-autonomous and motivational modality for engaging in large quantities of upper limb therapy [66, 106, 123]. The spectrum of technology used within these fields to promote clinical improvements in stroke populations is diverse. This can range from complex assistive robotic systems [55, 110] to gaming activities that run on low-cost hardware [15, 107, 135]. More recently, advances in the technology used for commercial gaming devices have led to a convergence of upper limb rehabilitation and commercial off-the-shelf video game consoles. Systems such as the Nintendo Wii and Playstation II EyeToy deliver low cost virtual reality and report significant improvements in participants' functional recovery [24, 106]. This approach may provide a method for increased patient access to additional therapy in clinical settings and compliance in home-based exercise [66, 106].

In this book chapter we present a review of methods used to incorporate video games in upper limb therapy, with a particular focus on studies that demonstrate clinically significant improvements in motor function. In order to do this, we permeate boundaries between the fields of Robotics and Virtual Reality in order to examine trends in design and implementation of gaming activities. Although the systems discussed in this chapter are unlikely to represent the complete spectrum of video games in upper limb rehabilitation, this survey is representative of the current state of the art. We start by presenting a background on the rehabilitation of stroke, followed by a discussion on the principles that drive the development of games for stroke populations. Subsequently, we review the field of robotics and video games, paying attention to how different approaches demonstrate clinically significant improvements. We discuss the use of virtual reality-based interventions and the development of serious video games for rehabilitation. Finally, we report on studies implementing commercial off-the-shelf devices as therapeutic tools.

18.2 Upper Limb Impairment and Therapy in Stroke

The neuropathological underpinnings of a stroke typically come in one of two forms. An ischemic stroke accounts for 87 % of strokes in the world [103], and entails the formation (embolus), or the transportation (thrombosis) of a blood clot to the brain [47]. Hemorrhagic stroke arises when there is bleeding in the brain caused by a ruptured aneurysm, or an arteriovenous malformation [132]. Prognosis for both ischemic and hemorrhagic conditions typically results in varying degrees of localised damage to the brain tissue. This is a result of the blood supply being cut off to the grey matter, leading to premature cell death known as an infarct.

A common problem faced by survivors is an inability to properly control movement and function in one side of the body [18, 122]. Unilateral muscle weakness known as hemiparesis; or more severe paralysis called hemiplegia, is a secondary result of damage to the motor pathways in the central nervous system. The presence of motor impairments post-stroke suggests a lesion has encroached on motor areas, or damaged the white matter that projects into the spinal cord reducing descending corticospinal drive [69, 127]. Consequently, a patient may experience a reduction in the ability to modulate appropriate force in the upper and lower extremities. Approximately 85 % of acute stroke survivors experience some form of paretic symptom [63, 87]. The severity of impairment can drastically vary and some studies suggest there may be a causal relationship between the size, location of the lesion and resulting level of disability [17, 67, 117]. Motor function deficits typically manifest on the contralesional side of the body. A lesion in the motor area of the left hemisphere will show paresis on the right side of the body and visa-versa. However, this is not always the case and although less reported, ipsilesional impairments may be present [61, 130, 133].

No other chronic disease causes a greater range of disabilities or greater disability impact than stroke [3, 60]. Activities requiring fine motor control, such as driving, using the toilet and eating, can become challenging and frustrating exercises [19, 68]. For example, a recent study reported that 30 % of stroke patients are unable to dress themselves 2 years after onset [126]. Variable levels of spasticity, or resistance to movement, present in 19–38 % of survivors may further complicate functional movement in the upper limb [13, 128]. Gross motor movements, including walking are frequently affected and can represent a heightened risk of falls and significant increase in mortality [71, 121]. Deficits in attentional resources such as hemispatial neglect are also common, whereby a patient is unable to cognitively attend to one side of their visual field [91]. Psychosocial symptoms are many, with 40 % of survivors finding post-stroke fatigue the most distressing aspect of recovery, as it interferes with normal psychological and physical function, as well as creating a barrier for engagement in therapy [52, 81]. Moreover, co-morbidity with other psychological disorders, such as depression and anxiety, is particularly high [7, 41]. Collectively, the spectrum of disabilities associated with stroke presents a significant challenge for the management of care for the healthcare provider and barriers for the patient.

At present, there is no standard approach to the rehabilitation of upper limb stroke impairments. Consensus on the efficacy of any single strategy for rehabilitation being superior is disparate, a consequence of the distinct lack of adequately powered randomized control trials in this area [94, 129]. Evidence for conventional therapy is strong and involves self-range and active range of motion strengthening exercises in the affected limb [92, 120]. Another popular method gaining momentum in clinical settings is Constraint Induced Movement Therapy [35, 116]. In both cases, these therapies rely on large volumes of repeated task-specific movements with the paretic limb in order to induce functional improvements in motor control. This task-specific practice interacts with the cortical mechanism of neural plasticity in the motor cortex [51, 114]. Neural plasticity is described by Cramer [22] as the ability of the nervous system to respond to intrinsic or extrinsic stimuli by reorganizing its structure, function and connections. In the case of rehabilitation for motor impairments, it is the adaptation of unaffected areas in the brain compensating for, and taking over, the function of the lesioned areas.

It is not possible to quantify how many movements a patient must carry out in order to facilitate neural plasticity and aid motor skill reacquisition [94]. However, it is known from rodent studies that three hundred to four hundred repetitions create observable changes in the motor cortex in rats [56]. In stroke, data on treatment dosage from a large scale Cochrane meta-analysis identified a positive correlation between dose and functional outcomes, suggesting it is necessary for a patient to participate in over 20 h of training to significantly improve limb function [129]. For a healthcare provider, meeting this level of intense motor practice in therapy sessions can be a considerable challenge. A recent study observing 312 therapy sessions in North America and Canada reported that the average number of repetitions per session was 32 [64]. Given the high cost of one-to-one therapy sessions, optimal treatment cannot always be provided in-house. A common solution to this problem is prescribing home practice routines to the patient, consisting of task-specific exercises to facilitate their outcome goals [20]. However, these routines are frequently criticized for being tedious and boring. For example, traditional activities may include stacking items and cleaning surfaces with a cloth for extended periods of time (daily). Data suggests that only 31 % of patients carry out home-based exercise routines as recommended [108].

18.3 Video Game Design in Upper Limb Stroke Research

The use of video games is common in both robotic and virtual reality based approaches to rehabilitation of the upper limb [66, 106, 123]. The integration of play into therapy can transform what may otherwise be considered laborious repetitive movements into enjoyable experiences. Support for this is representative in satisfaction feedback measures across several studies [49, 66, 82, 99, 112, 134, 135].

Modern video games aim to engage the user in extended periods of play whereby large volumes of repetitive button presses are required to complete on-screen objectives. The mechanisms which mediate the upkeep of this behavior are a complex and diverging multidisciplinary study in itself [105]. In the case of stroke, several papers have elucidated core principles important to the design and development of games for this population. Jung et al. [53] discussed how identifying the target audience, providing feedback and intuitive visibility of game objectives are fundamental in stroke games, whereas Goude et al. [36] developed a taxonomy of impairments and outcome goals that are relevant issues in stroke for game designers. Alankus et al. [5] stressed the need for accessible and sensitive games able in order to facilitate the diverse spectrum of impairment associated with post-stroke recovery. Burke et al. [11] describe meaningful play and challenge as two important issues in maintaining interest and upkeep in stroke gaming.

Common discourse in the literature for stroke game design is found in two salient constructs; that of feedback and challenge. Feedback is the mediator between the system and player, and is known to be an important motivator for motor learning [2]. Feedback allows a participant, or a clinician, to synchronize long and short term goals in motor function with in-game measures of performance. Studies often report how explicitly identifying and achieving goals was fundamental in tapping into a participant's competitive drive and helped maintain engagement in a video game intervention [11, 12, 76, 82]. In support of this, trials conducted using Constraint Induced Movement Therapy have stressed the need for motor goals in therapy settings to be obtainable, specific and realistic to the participant [35, 116]. Feedback may also evoke negative responses from a player and it is important to consider how feedback is delivered following in-game failure. Self-efficacy is a serious problem for stroke survivors. For the motor impaired patient, the impact of stroke may drastically alter their ability to carry out every day activities that previously would require little effort or thought [124]. A recent qualitative report on off-the-shelf Wii games for stroke suggested feedback in commercial games used for rehabilitation purposes often undermines or upsets participants because the level of ability in motor control is less than that of a healthy player and the feedback does not adequately reflect this [45].

Finally, facilitating an appropriate level of challenge for patients with upper limb impairments can be difficult. As discussed, the range of disabilities present in this population are extensive and finding sensitive difficulty gradients to suit all participants requires flexible game mechanics capable of responding to a wide variety of abilities. Common in stroke games are settings that modulate the speed, size and location of various game objectives. Calibrating difficulty is typically done in pre-intervention trials or via a clinical assessment. Of note is the Rehabilitation Gaming System's [15] online difficulty module that adapts the challenge in real-time responding to a player's game performance.

A number of underlying principles based on sensorimotor and neurological rehabilitation studies are applied in the development of custom upper limb stroke games. As discussed, motivation and the factors that maintain it are central to promoting better patient outcomes. Achieving optimal levels of arousal and motivation have been linked to higher rates of neuroplasticity and more effective motor learning [37]. Furthermore, optimizing the dose of repetitions condensed into a rehabilitation activity is important [129]. A balance must be struck between intensity and the safety of the participant in order to avoid overuse injuries common in video gaming literature [9, 21]. Often video games will include a representation of a player's limb(s) [15, 23, 74]. The use of a graphical representation of the upper extremities builds on the paradigm of the motor neuron system as a method of augmenting neuroplasticity. Seminal research by neuroscientist Giacomo Rizzolatti proposed that the mirror neuron system activates in both goal-orientated action execution and action observation [101, 102]. Thus, the process of motor learning can occur as a result of watching, as well as physically performing, a movement. By including a virtual representation of a limb, it is hypothesized that the efficacy of a repetition-based exercise can be augmented with motor learning induced by the motor neuron system.

There is some evidence that suggests bimanual training may provide an effective method of facilitating cortical reorganisation after stroke [104]. Both longitudinal and hyperacute fMRI studies report that recovery of motor skill post stroke frequently exhibits a transfer of motor processing from the damaged ipsilesional motor cortex to the contralesional hemisphere [38, 97]. It is hypothesized that bimanual training may help facilitate this transfer [104]. However, due to a lack of robust evidence, the precise power of bimanual training in the reacquisition of motor skill is yet to be fully understood. Despite this, several of examples of bimanual approaches to motor training exist in the literature [15, 55, 74, 134].

18.4 Robotics and Video Games in Upper Limb Stroke Research

The initial use of video gaming as an activity for upper limb stroke rehabilitation was linked with interventions using assistive robotic technology. In robotics, video games are used as a method of increasing the amount, and enhancing compliance, to therapeutic upper limb movements. Semi-autonomous operation is common and dedicated supervision by a fully trained physical or occupational therapist is not always required. Therefore, some studies suggest that robotics presents a method of increasing access to therapy [50, 55]. In this section we cover a selection of studies that implement gaming activities alongside robotics.

Assistive robotics has been shown to help augment conventional therapy [78, 90]. Its efficacy as an approach has been reported in trials with both acute [55, 59, 125] and chronic phases of stroke [26, 50, 72, 85, 110]. The question of whether robotic-assisted technology can outperform conventional therapy on clinical measures is not clear. A recent large scale randomized control trial, including 127 patients, found that there are no significant differences on functional upper limb measures after 12 weeks of robotic versus conventional therapy [72]. However, at a 36-week follow up, significant improvements were found on Fugl-Meyer scores. Moreover, a Cochrane review suggested robot therapy may induce better rehabilitation outcomes representative in studies including measures of activities of daily living [79]. Robotic rehabilitation systems help guide hemiparetic movements actively if adequate motor control is unavailable and show particular promise for patients who may have more severe upper limb impairments [78]. Robotic therapy assists in providing higher level doses over time than that of conventional therapy; frequently studies report, on average, five hundred repetitions per session [4, 28, 32]. Additionally, robotics can facilitate real-time limb positioning and force measurements. However, robotics is an expensive technology, that can typically require a costly initial investment.

The MIT-MANUS is one of the earliest robotic devices integrating custom video gaming as a rehabilitation activity [4, 57, 58, 98]. The MIT-MANUS is a two degrees of freedom robot designed to rehabilitate movements of the upper arm [57]. Its success as a clinical device for treatment has been reported in a randomized control study of 76 acute patients [4, 59, 125], and trials of chronic stroke [26, 31, 32, 33, 77]. Early versions of gaming activities are described briefly in a chapter by Reinkensmeyer et al. [98] as including drawing circles, stars, squares and diamonds while navigating through graphical windows. Interaction with the game objectives requires the participants to move the robot end-effector to various target locations that recruit proximal muscle activation in impaired limb. The MIT-MANUS can either actively guide or passively provide anti-gravity support to complete a gaming objective. Krebs et al. [58] reported the outcome of twenty subacute hemiparetic participants who engaged in either an MIT-MANUS based intervention (active setting) or a control robotic therapy group (passive setting) over a 7 week period. Clinical measures of functional improvement in the upper limb were tested pre-post and for twelve of the participants at a 3 year follow up point. Measures included the Fugl-Meyer, Motor Power for shoulder and elbow, Motor status score for shoulder and elbow and Motor Status Score for wrist and fingers. Krebs et al. [58] reported that stroke patients who were treated daily with the robot-aided therapy had improved outcome in motor activity specific to the muscle groups trained compared to the sham therapy group at hospital discharge. Results of the robot aided therapy group at recall showed improvements almost twice that of the sham group 3 years post-intervention.

ARMin is a more recent, and, compared to the early MIT-MANUS device, technically more advanced exoskeleton robot which has reported initial success in small scale trials with chronic hemiparetic participants using simple interactive video games [84, 85, 110]. It is a six (ARMin II) [84, 110] or seven (ARMin III) [85] degrees of freedom robot capable of moving shoulder, elbow and wrist joints. There are two games tested with this system by Staubli et al. [110] in chronic hemiparetic stroke patients. First, a ball game where a patient must move a virtual handle on the screen in order to catch a ball rolling down a virtual ramp. If the patient is unable to guide the handle robotic assistance is initiated. The colour of the handle turns from green to red when robot-assistance is provided. Second, a labyrinth game where a patient must direct a ball from the bottom to the top of the labyrinth. The ball is guided by a cursor which must be moved accurately through the labyrinth without making contact with a wall. If contact with a wall is made, the simulation restarts. Both games provide progressive difficulty settings modulating the arm weight compensation, vertical support, number of joint axes involved, working space and sensitivity of the wall. In this study, participants received ARMin II therapy over a course of 8 weeks. Two patients received 4 h, and two patients received 3 h training sessions a week. The authors reported significant improvements on the Fugl-Meyer score for the upper extremity assessment in three of the four participants. Furthermore, at a 6 month follow up, these participants continued to exhibit trends of improvement.

In Kim et al. [55] the UL-EX07 robot was combined with eight interactive video games as an intervention for 30 hemiparetic participants. The UL-EX07 is a seven degrees of freedom robotic device which can support 97 % of the upper limb work space [93]. This study explored whether bimanual or unilateral approaches provided any additional benefits on clinical outcome measures. Four of the games developed for this study were purely diagnostic tools; these included flower, paint, joint movement and reach. The remaining four: 'pong', 'circular pong', 'pinball' and 'hand ball' games, were all able to accommodate either bimanual or unilateral therapeutic movements. Difficulty using the UL-EX07 is modulated by adjusting the level of compensation for gravity and active assistance provided by the robot. Participants played the eight games over twelve sessions, each lasting an hour and a half under the supervision of a research assistant. The authors reported all participants demonstrating a four point gain on the Fugl-Meyer (it should be noted that a change of five points for upper limb is considered a minimally successful clinical change). However, the authors found no significant differences between bilateral and unilateral training on four collated evaluation metrics including the Fugl-Meyer. Improvements in wrist pronation-supination for the bimanual training group were found in kinematic variables more than twice than that of the unilateral group. Kim et al. [55] suggested this could be due to the UL-EX07 not administering active wrist motion facilitation, whereas the bimanual training group could support the impaired limbs wrist joint with their unaffected arm.

In stroke, sensorimotor impairments are more pronounced in the distal muscles of the upper limb that require higher corticospinal drive [69, 127]. Hemiparetic patients frequently struggle with the appropriate modulation of force when trying to carry out fine motor movements like grasping. For robotics, integrating technology which can facilitate movements in the smaller muscle groups, such as those found in the hand, is hard. Merians et al. [80] addressed this issue reporting an intervention using video games for enhancing the rehabilitation of the hand, as well as the arm. In this approach, hand specific training games integrated a Cyberglove for tracking and a CyberGrasp; a robotic finger manipulation exoskeleton for the Cyberglove. Arm training in this study utilized the Haptic Master, a force controlled robot, able to provide force feedback against the arm on the horizontal plane involving pronation/supination. Four games were tested and are summarized as follows. First, "Plasma pong" is a hand training game recruiting shoulder flexion to move a paddle in space with the objective of hitting a randomly moving ball. Engagement with the ball was triggered by rapid extension of the fingers. Second, “Hummingbird” is a hand training gaming immersing the participant in a simulated environment whereby he/she is required to transport the arm and intercept a randomly moving hummingbird with a pincer grip grasp before releasing it to continue on its path. The “Virtual Piano” featured a completely simulated piano for hand training and could be operated with or without the assistive CyberGrasp robot (another study using the hand piano can be seen in [1]). The “Hammer Task” is an arm training simulation which recruits three dimensional reaching and finger flexion. The arm must be transported towards a virtual wooden cylinder. When the virtual limb reaches the cylinder, repetitive finger flexion hammers the object into the floor. In Merians et al. [80] twelve chronic hemiparetic patients who were not receiving any other therapy, engaged in 2–3 h training, four times a week, for 8 days. Each session time was divided equally between all four games. Initial training lasted 2 h and was increased by increments of 15 min during week one. By week two, training time remained at 3 h for all sessions. A number of kinematic measures were collected, analyzed and reported in this chapter. Robust significant improvements on the Wolf Motor Function and Jebsen Test of Hand Function were reported.

Passive robotic devices do not guide movements in the impaired arm. Instead all movements are the result of voluntary muscle activation with adjustable weights, or elastic bands to compensate for gravitational forces. As a result of this, these devices are often suggested to be both cheaper and safer than conventional active robotic devices. In Housman et al. [50] the results of an intervention using a passive robotic exoskeleton called T-WREX combined with Vu Therapy games was reported in chronic stroke participants. The T-WREX is a five degrees of freedom arm orthosis that uses elastic bands to compensate for gravitational forces. Vu Therapy games were developed at the University of California and include grocery shopping, cleaning a stovetop and playing basketball. Prior to each session Vu Therapy games undergo a software-based calibration by a clinician which adjusts difficulty accordingly. In Housman et al. [50] a randomized control trial featuring twenty-eight moderate to severely impaired hemiparetic stroke patients compared the T-WREX and Vu Therapy games to tabletop based exercises, common in conventional therapy. Each group took part in twenty-four, 1 h treatment sessions and was evaluated pre/post and at a sixth month follow up. User satisfaction scores reported 90 % of T-WREX participants preferred this method of therapy over conventional tabletop exercises. Additionally, they reported T-WREX therapy as less boring, less confusing and easier to track their progress with. Fugl-Meyer comparisons reported a trend for improvement at post intervention, and a statistically significant improvement at a 6 month follow up in favour of the T-WREX. Authors concluded that T-WREX therapy may be appropriate for moderately to severely impaired hemiparetic patients and showed particular promise as a method of reducing therapist contact with less than 4 min of direct contact per hour reported.

More recently, Steinisch et al. [111] reported a study implementing a passive robotic device with five video game simulations and an online high resolution EEG device for recording cortical activity throughout treatment phases. This approach used a Trackhold robot with seven degrees of freedom. All games require movement of the Trackhold end effector to complete game objectives. Games included "Sponge", whereby the participant must reveal a picture by wiping the screen with a virtual sponge. "Bug hunt" included a virtual hand holding a swatter, requiring the participant to intercept a randomly moving bug. Adjusting difficulty in this game was done by increasing or decreasing the speed with which the bug moved. "Twirl" requires the player to move the arms in a circular path indicated on the screen whilst keeping the cursor within a blue segment represented on screen. Difficulty was modulated by the size of the blue segment. "Grab 2D" required the participant to pick up a virtual object and transport it over to an avatar sitting opposite the player on a table. "Grab 3D" required the participant to transport a virtual hand in a linear motion to an end point signified by a moving butterfly. Similarly to Bug hunt, modulation of difficulty was adjusted by the speed of the butterfly. Two healthy participants were tested in three 25 min sessions three times a week for 4 weeks. EEG data saw activations in cortical areas in line with current literature and theoretical predictions.

18.5 Virtual Reality and Custom Upper Limb Video Games

A development in novel strategies for providing rehabilitation is the use of virtual reality as a modality for repetition practice [44, 49, 66, 73]. Much like robotics, virtual reality provides engaging therapeutic motor practice through gaming activities. However, virtual reality applications are typically lower in cost than their robotic counterparts and show potential as telerehabilitation devices. Rehabilitation in a virtual environment may present several advantages over conventional therapy. First, the use of rich, multisensory, graphical representations of real world scenarios can provide a more cognitively stimulating and salient experience for the patient. Second, task practice in a simulated environment may provide more ecological validity than practice performed in conventional therapy sessions [100]. Finally, upper limb movements in a virtual environment allow kinematic performance data to be extrapolated for both the participant and clinician.

Player interaction in a virtual environment is typically achieved by video capture, motion sensors, or a combination of both. Virtual reality can be immersive or semi-immersive, depending on the device used to provide visual feedback. Fully immersive systems commonly use head mounted displays that are sometimes associated with cyber sickness in the elderly populations [6, 70]. Semi-immersive systems use a monitor to provide visual feedback. Recently, the use of low-cost off-the-shelf hardware in games developed for stroke is common [23, 131]. These devices are able to offset the cost of laboratory grade sensor technology, by implementing low cost alternatives such as the Nintendo Wii remote.

Sucar et al. [113] reported a trial comparing a stroke video game system called Gesture Therapy versus conventional therapy in chronic stroke. Gesture Therapy is a low-cost camera based system that tracks a hand grip held by the participant in their impaired arm. Eight games recruiting task specific movements were practiced in this trial including: shopping in the supermarket, making breakfast, playing basketball, cleaning the windows, cleaning the stove, painting the walls, preparing a hot dog and driving on the highway. The system produces feedback in the way of progress charts and performance scores after each game. Twenty-two participants were assigned to either the experimental or control condition. Training was completed in fifteen 60 min sessions over 5 weeks. A motivation survey was administered and showed participants who took part in gesture therapy demonstrated better scores in interest and a greater perception of effort and utility. Both groups exhibited significant improvements on the Fugl-Meyer and Motricity scores post treatment. However, no statistically significant differences between improvements were reported between groups.

In Ma and Bechkoum [74] a selection of serious games developed by the University of Ulster targeted at enhancing duration, dexterity and range of motion were tested in chronic hemiparetic stroke participants. All games featured a fully immersive virtual environment delivered via the use of a head mounted virtual reality device. Additionally, a set of motion sensors and two data gloves were used to track upper limb movements. Two different functional tasks called reach and retrieve and wrist extension provided training in reaching, grasping, release and rotation of the wrist (these games are discussed further in [23]). Two games called fishing and catch-the-oranges trained bimanual motor control (catch the oranges has a unilateral alternative). One unilateral game called 'Whack-a-mouse' trained gross motor movements. All games were developed with sensitive difficulty settings capable of meeting a variety of needs in the facilitation of a challenge for the patient. 'Fishing' included a virtual representation of the hands. Feedback in the form of online performance scores provided patients with progressive targets in line with functional gains in their paretic limb. Ma and Beckhoum [74] tested the efficacy of these serious games on a small sample of four hemiparetic patients over the course of 10 supervised sessions. A further four participants were assigned to a control group who did not engage in any video gaming. Both groups were undergoing conventional therapy whilst participating in the study. All participants showed significant improvement over the testing period on the Motoricity Index. Participants who engaged in serious game therapy had a statistically significant improvement on the Motricity Index in comparison to the control group.

In Crosbie et al. [23] custom stroke games developed by the University of Ulster are described (included in these were the previous games in Ma and Beckhoum [74] which we have already discussed earlier in this book chapter). Crosbie et al. discussed the development of a collection of low-cost webcam and sensor-based video games targeting bilateral gross motor control in both the paretic and unaffected limb. 'Rabbit Chase' is described as a training game that projects a video-captured representation of the player on a screen with four rabbit holes and a virtual rabbit running in and out of these holes. The holes are arranged in the vertical and horizontal planes. The player must move one arm to a hole which represents the rabbit's starting point and they then must anticipate the rabbit's path to an exit hole, transporting the other arm to this target location. Similarly, 'Arrow

Attack' uses a similar web camera projection and four boxes arranged on the screen across the horizontal and vertical planes. The participant must correctly place their hands in the boxes as cued by coloured arrows. Difficulty in both games can be adjusted by adapting the speed of the challenges and the distance of each target (hole or box) from the other. Audio and visual feedback is present in-game following successful hits. The final game presented in this chapter uses Nintendo Wii remotes and sensor to interact with a virtual vibraphone presented on screen. The player can freely play the vibraphone with two virtual mallets or follow instruction from the computer on what sequence of keys they must strike to play a preselected song. The participant strikes the keys by aiming at the target and pressing a button on Wii remote. In [24] these games, along with the games described in Ma and Beckhoum [74], were tested in a pilot randomized control study in eighteen hemiplegic participants. In this study the experimental group experienced 30–45 min of the games, three times a week over a 3 week period. The control group received conventional therapy for the same amount of time over the study period. Both experimental and control groups demonstrated small, yet non-significant improvements on the Motricity Index and Action Research Arm Test. Crosbie et al. [24] concluded that future work would require seventy-eight participants to adequately power a randomized control trial in this population using these games.

Wijck et al. [131] reported on the development of a musical video game using the Wii remote control as an input device for motor therapy. The game is described as a tap-tempo paradigm, where the participant is required to move a cursor to one of a number of target circles with the impaired arm. The circles highlight in synchronization with a song's tempo. Difficulty can be adjusted depending on the tempo subdivision the target synchronizes with (for example, quarter note, eighth note, sixteenth note), the distance between targets, and the amplified gain between the participant's movements and the cursors. The protocol allows the user to select a piece of music they wish to play along to. The song is preprocessed by the operator, extracting the tempo and rhythm information. This chapter featured no experimental participants.

In Kwon et al. [62] a randomized control trial in acute patients undergoing IREX virtual reality therapy and conventional therapy, versus conventional therapy alone, is presented. The IREX is an established clinical virtual reality tool developed by GestureTek that offers twenty three rehabilitative games, five of which are specific to the upper limb. IREX uses a video camera and Cybergloves to track movements in the upper limb. The system has a number of bimanual and unilateral upper limb games and provides a variety of feedback including scores and progress charts. In Kwon et al. [62] five games were selected including 'Bird and Ball', 'Drum', 'Coconutz', 'Soccer' and 'Conveyor'. All participants underwent conventional therapy 70 min per day, 5 days a week for 4 weeks. The IREX experimental group received an additional 30 min of virtual reality therapy on the same days as conventional therapy. Both groups reported pre- and post-test significant improvements on the Fugl-Meyer. The IREX condition additionally reported improvements on the Manual Function Test, whereas the control did not. The authors reported no significant differences between groups on outcome measures. Kwon et al. [62] concluded that the IREX can enhance upper limb function in conjunction with conventional therapy.

Hoermann et al. [48] tested an Augmented Reflection Technology device and memory game called the Theramem. The system requires the participants to place their hands on the floor of a large black box obscuring them from eyesight while a virtual representation of their hands is displayed on a monitor. They interact with twenty four tiles which are displayed across two monitors, with twelve tiles represented on each screen. The game requires the participant to find matching pairs of plants across the two screens by turning over one tile at a time (further information on the system can be found in Regenbrecht et al. [96]). The Theramem was tested with five hemiparetic patients. Three participants were severely impaired with scores of 0 in the Fugl-Meyer and Motor Assessment Scale, while two were moderately impaired. Participants engaged in twenty 60 min intervention sessions while supervised by a physiotherapist and experimenter. Prior to each session, hand exercises were administered by the clinician to reduce spasticity in the participants affected limbs. The two moderately impaired participants showed clinically significant gains in hand function on the Fugl-Meyer and the Motor Assessment Scale. Participants reported in post intervention interviews that the Theramem should be incorporated into therapy sessions and expressed interest in continuing this type of intervention.

Cameirao et al. [15] presented a robust randomized control study using the Rehabilitation Gaming System in acute phase stroke patients (other studies using the same system can be found in [15, 89]. The Rehabilitation Gaming System uses two data gloves to capture finger flexion, a vision-based analysis and tracking system to co-ordinate player hand movements with an on-screen representation of the upper limbs and a personalized training module that adapts online difficulty of the task to the performance of the user. The video game facilitates a high volume of bimanual task practice. This task practice takes the form of interacting with spherical objects travelling towards the participant at speed. Interaction involves a range of facilitative functional movements. As each sphere comes towards the participant, he/she is required to reach for the object and perform either a hitting or grasping motion. Depending on the setting and difficulty parameters the participant is then required to transport and release it in a corresponding colour-coded depository. Difficulty is modulated by the speed, range of movement, method of interaction and time interval between spheres. Adaptation of difficulty is done in real-time, so, if the user intercepts more than seventy percent of spheres the setting is increased, if the user intercepts less than fifty percent the difficulty is decreased. Moreover, the difficulty for each arm is independent, meaning that the unaffected limb is not held at the same difficulty setting as the paretic limb. Cameirao et al. [15] recruited eight acute hemiparetic and a further nine control participants. The controls were split into two groups; five were assigned to an intense occupational therapy group and a further four played games on the Nintendo Wii that did not have a virtual representation of the upper limbs. The Wii group was included to control for placebo effects relating to video gaming as a modality and to test whether the virtual representation of the upper limbs apparent in the Rehabilitation Gaming System and not in the Wii games created a significant improvement in functional outcome measures. In addition to standard rehabilitation, patients were assigned three weekly sessions of 20 min each of a given treatment condition over a 12 week period. Functional outcomes of the intervention were assessed using a range of measures relating to different aspects of motor impairment and function. Assessment on these measures was performed by a clinician blinded to group allocation at weeks five, twelve and with a twenty four week follow-up. A number of in-depth analyses were carried out on data points validating the use of the Rehabilitation Gaming System in this chapter. For the sake of brevity, the reviewer has summarized findings as follows; the Rehabilitation Gaming System in contrast to control groups showed significantly faster improvement over time in paretic arm function in the Fugl-Meyer, Barthel Index and Motricity index during the treatment period. Additionally, after the ninth week of treatment, statistically improved movement speed for the paretic limb was found in favour of the Rehabilitation Gaming System. Between group comparisons found significant improvements for the arm sub-test of the Fugl-Meyer. However, no significant group comparison was found in the hand sub-test. Finally, Cameirao et al. [15] discussed whether the lack of improvements on the hand sub-scale could be due to a lack of haptic feedback, in so far that the participants were grasping virtual spheres and not actual objects.

18.5.1 Commercial Off-the-Shelf Video Games for Upper Limb Stroke Rehabilitation

Access to video game based interventions for the upper limb impairments in stroke were typically conducted in laboratory settings, and thus out of reach for the vast majority of motor impaired survivors. However, technological advances in commercial off-the-shelf gaming consoles have been embraced by the rehabilitation community as a novel therapeutic tool. Commercial off-the-shelf video game systems have been employed to treat Balance impairments in stroke [8, 27, 43], increase cardiovascular fitness in older adults [40], and improve psychosocial functioning in the elderly [16] The low cost, and ease of access inherent in modern video game systems has facilitated a boom in use of these for both clinicians and research groups. A gaming system can be purchased by a care provider, or patient, at a fraction of the cost of laboratory grade virtual reality stroke rehabilitation systems and can easily be installed in outpatient homes as a form of telerehabilitation.

Current approaches in commercial off-the-shelf gaming for upper limb stroke are paving the way for stock systems such as the Nintendo Wii [107, 135], the PlayStation II EyeToy [95, 99], and the CyWee Z [46] in motor therapy. Most studies are small in power, typically including 5–20 participants, and as such should be treated with caution when generalizing findings to the wider stroke population. In general, commercial off-the-shelf video games systems are described as a low-cost solution to the issue of access to virtual reality rehabilitation. The use of these devices is often discussed to present an additional risk of seizures in the stroke population [106, 109, 135]. Nintendo has suggested that the risk of a seizure in healthy populations is 1 in 4000 [88]. In stroke, data suggests that survivors have approximately 11.5 % risk of a single or recurrent seizure in the first 5 years following onset [14]. While this area is still in its relative infancy and currently lacking the depth of robust studies to adequately clarify how, and which technologies can best be employed in upper limb stroke, we introduce the current state of the art as reported in this area.

The PlayStation II with the EyeToy motion camera entered the market in 2003, and was one of the first commercially available motion based video game systems used within upper limb rehabilitation studies [34, 95, 99, 134]. The PlayStation EyeToy is a mounted motion capture device for the Sony PlayStation II. As a peripheral device, games for the EyeToy are limited, and studies in this area use mini games found in the Play series; including 'Play 1', 'Play 2', 'Play 3'. The EyeToy operates by projecting a video-captured representation of the player onto a monitor in order to interact with game objectives. Gameplay in the 'Play' series is elementary, consisting of target-driven movements to complete different objectives. Reinthal et al. [99] have suggested that the EyeToy can be an effective piece of technology to use when a patient struggles with more complex cognitive demands associated with off-the-shelf games. Moreover, the EyeToy can be used when a patient cannot produce the required force to activate a response from accelerometer-based controllers, such as the Nintendo Wii remote.

Rand et al. [95] presented a paper describing three sequential studies testing the feasibility of a Playstation II and Eyetoy as a rehabilitation device in older adults. The aim of this study was to provide information on the EyeToy as a therapeutic device in comparison to an established clinical Virtual Reality tool named the IREX. The IREX is a virtual reality rehabilitation device that costs approximately $13,000. All studies followed an experimental protocol whereby participants would play three games on the Playstation II, namely: 'Kung-Foo', 'Keep-Ups' and 'Wishy-Washy' (mini games within the Play game) and two games on the IREX virtual reality rehabilitation system; 'Soccer' and 'Birds and Balls'. Procedurally, participants were allowed 60 s practice and 180 s of play on each game. Performance scores reported by each game were manually recorded. After each participant completed testing, ratings of presence, perceived exertion and enjoyment were collected via questionnaires. The first study included thirty-four healthy participants with a mean age of twenty-six. Results indicated no significant differences between perceived presence in the two devices or games. A significant difference in enjoyment scores was found in favour of the game Kung Foo. The IREX game Bird and Balls was reported to be significantly easier than Soccer, Wishy-Washy and Kung-Foo. The second study recruited a further cohort of older adults with a mean age of seventy and compared game performance with the young adults in the first study. Results reported differences in performance in favour of the younger participants. However, no significant differences were found between perceptions of presence, enjoyment or exertion. Finally, study three tested the protocol on twelve stroke participants, seven of which were chronic and five in subacute phases. Results indicated all stroke participants highly enjoyed the games. The chronic group enjoyed Kung-Foo more than Wishy-Washy and rated perceived exertion as higher for Kung-Foo. All participants reported symptoms of fatigue in their affected upper limb as a result of playing the EyeToy. Authors reported five subacute participants highly enjoyed the modality of therapy and would happily repeat it. However, two participants were visibly frustrated as they were unable to produce the required movements in their impaired limb in order to interact with the game tasks. Rand et al. [95] concluded that the EyeToy was suitable for higher functioning chronic stroke patients who were able to engage in play and benefitted from this form of virtual task practice.

In a randomized control study by Yavuzer et al. [134] the PlayStation EyeToy was tested as a rehabilitation device with a cohort of twenty hemiparetic inpatients. Participants were within 12 months since an onset of stroke (mean time 3.9 months) and receiving conventional rehabilitation of 2–5 h a day, 5 days a week, over a 4 week period. The RCT consisted of allocation to one of two groups; engagement in 30 min of EyeToy video gaming a day, 5 days a week, for 4 weeks; or a control group, who for the same period watched the video games with no active physical engagement. Analysis of post intervention results found no significant improvement for the Brunnstrom stages for hand or upper extremity. However, participants in the EyeToy group showed a significant improvement on the Functional Independence Measure of self-care ability in comparison to the control. Yavuzer et al. [134] suggested duration of the intervention (10 h) may not have been long enough to produce functional improvements on the Brunnstrom stages. The authors discussed whether Brunnstrom stages had the magnitude of sensitivity necessary to detect changes within a 2 week intervention of this kind. The Brunnstrom stages contain six sequential and progressive stages of motor recovery. Changes in this measure from one stage to the next would suggest accentuated improvements likely not obtainable with a protocol of this kind in a 2 week intervention. Furthermore, Joo et al. [135] questioned whether the inclusion of the Functional Independence Measure of self-care ability, an inventory which includes 126 items including locomotion, social cognition, and sphincter control, is suitable as a primary outcome measure in an upper limb validation study.

Aside from the Playstation II EyeToy, the more recent Nintendo Wii received a lot of focus as a potential device for use within upper limb rehabilitation. The stock system comprises of the console and the Wii remote which uses a combination of accelerometers and infrared sensors to detect movement and its position within a 3D space. Unlike the EyeToy, which is a peripheral device for the PlayStation II, Wii games by default require motion input, leading to a wider breadth and diversity of potential games for rehabilitation providers and enthusiastic patients alike. Overuse injuries, termed "Wiiinitus", are common in healthy populations who experience Wii gamepay for the first time [9]. Therefore, studies that investigate the Nintendo Wii in stroke populations are careful to mix up the activities and provide rest breaks while playing on this console [82, 106].

In a seminal randomized control study, Saposnik et al. [107] recruited twenty acute hemiparetic participants to test the feasibility of the Nintendo Wii. An experimental Nintendo Wii condition was compared to a control group who engaged in a course of recreational therapy. The experimental condition engaged in supervised play of Wii Sports, and Cooking Mama while the recreational therapy participants played non-video games Jenga and Bingo. Feasibility was measured by time spent on activity (minutes) and adverse effects as a result of intervention measured by the Borg Perceived Exertion Scale [10]. Both groups were designated eight sessions lasting 60 min over a brief, yet intensive, 14 day period. Primary feasibility measures were analyzed at the close of the study and found no significant difference between time spent on activity between the groups (388 min in Recreational Therapy versus 364 in Virtual RealityWii groups), and reported no significant adverse effects on the Borg Perceived Exertion scale. Secondary functional measures were collected at a 4 week post intervention follow up, and recorded a significant improvement on the Wolf Motor Function Test for the VRWii group (-7.4s).

The use of the Wii as a therapeutic activity for early stage acute stroke was supported by Joo et al. [135] in a feasibility study with sixteen hemiparetic participants. In this protocol patients were recruited within 3 months of onset. Average time since stroke was 26 days. Participants engaged in six 30 min sessions over 2 weeks alongside standard conventional therapy. If patients were unable to hold the remote due to weakness or no grasp, strapping in the form of a custom fabric assist was applied. Clinical measures were collected pre and post intervention using the Fugl-Meyer Assessment, Motricity Index and a visual analogue score of upper limb pain. In addition to this, all side effects and adverse events were recorded by clinicians. Results reported a modest, yet significant, improvement on the Fugl-Meyer and Motricity Index. Changes in perceived pain pre and post intervention were non-significant and five cases of adverse effects relating to operation of the Wii were reported. These included two cases of lethargy and fatigue and three cases of mild pain and soreness in the limb lasting less than 1 day and not effecting participation in conventional therapy. Moreover, feedback from subjects showed 75 % of patients felt it was as useful as, if not better than, conventional rehabilitation. 81 % found it fairly to highly enjoyable and 87 % of participants wanted to continue these sessions as part of their rehabilitation programme.

In Neil et al. [86] a comparison of the intensity of movement between the Nintendo Wii and Playstation EyeToy was reported. Ten chronic stroke patients were age-matched with healthy participants and played 10 min each of four different games. Canoeing and Sword Fighting were selected for the Nintendo Wii and Wishy-Washy and Kung-Foo for the EyeToy (respectively). Intensity of movement was quantified via the use of accelerometers placed on the participant's wrists via a watch strap. Neil et al. [86] reported that for both healthy and stroke groups the Playstation Eyetoy elicited significantly higher intensity and overall upper extremity movement than the Wii.

18.5.2 Commercial Off-the-Shelf Video Game Systems as Rehabilitation Tools

More recently, the area of commercial off-the-shelf gaming devices for upper limb rehabilitation is beginning to see a shift from validation studies examining supervised play and its benefits, to a more in-depth investigation of how low cost gaming devices can be introduced to meet the specific needs of each participant [82, 99, 118]. Through more rigorous patient centered protocol these approaches aim to blend the advantages in cost and explore the boundaries of the devices as rehabilitation tools, rather than just a therapeutic gaming activity.

Mouwad et al. [82] reported an intensive 2 week intervention based on the temporal and intensity principles of Constraint Induced Movement Therapy [115]. In this approach the patient is given a Nintendo Wii and Wii Sports, in order to augment supervised practice in clinic with a home-based programme of task specific movements. Participants do not simply play the Nintendo Wii. Instead, the device is used as a rehabilitation tool, with specific motor control goals targeted at reinforcing appropriate and coordinated motor patterns [76]. Within a 14 day period, participants received 1 h supervised therapy using the Nintendo Wii on ten consecutive weekdays, bolstered by a progressive home-based protocol increasing from 30 to 180 min per day (for further details on this protocol see [76, 118]). Analysis of each individual patient's impairments was conducted at the start of the study and during the ten supervised sessions participants were set goals. These goals focused on in-game performance and improvements in the quality of movement associated with their impairments. Goals were collaboratively reviewed by patient and clinician after each session in a 'transfer package'. The aim of these sessions were to draw attention to the progress made and residual deficits still apparent in the paretic limb in order to discourage learned non-use and further motivate participants. Mouwad et al. recruited seven stroke participants and five healthy controls. Healthy controls were included in order to test whether the functional improvements were not due to skill acquisition or learning the Wii games. The experimental cohort included five chronic patients and one subacute with a mean time of 15.3 months since onset of stroke. Several of these participants found holding the Wii remote difficult due to weakness in the hand. For these participants allowances were made, by letting the non-affected arm be used in order to stabilize the controller and paretic limb. However, this assistance was progressively reduced and evaluated in each transfer package, with complete withdrawal being achieved by day fourteen. All participants saw functional motor control improvements in the upper extremity, range of motion was increased by 20.1° and 14.33° for passive and active movements (respectively). Significant improvements in mean Fugl-Meyer scores and a decrease in time required to complete to Wolf Motor Function Test were reported. Motor Activity Log of Quality of Movement scores improved significantly from a mean of 2.1 to 2.9 post-therapy, suggesting these improvements carried over movements required for everyday tasks. There were no statistically significant improvements for the control group.

Reinthal et al. [99] devised a game selection algorithm called the ENGAGE protocol capable of matching each patient's unique cognitive and motor deficits with appropriate gaming activity. The PlayStation EyeToy and Nintendo Wii were selected as the primary video game platforms. For the EyeToy, Play 1, Play 2 and Rock Band (using the Drum Set, and Guitar accessories) were selected; Wii Sports, Wii Resort and Wii Play were identified for use with the Nintendo Wii. Through a collaborative effort, mediated by therapists and researchers, a taxonomy of cognitive and physical demands required to play each game was generated. Features included identifying what joints and planes of motion each game involved and whether the task needed specific types of hand manipulation. Additionally, analysis of whether the games were continuous (such as Wii Sports boxing), or discrete (Wii Sports golf), and whether they required unilateral or bimanual dexterity (Rock Band drumming vs playing Rock Band guitar) was conducted. Sixteen hemiparetic outpatients receiving physical and/or occupational therapy were recruited in order to test the efficacy of selectively prescribing different gaming options to facilitate specific rehabilitation needs in stroke. Participants underwent an examination of the individual cognitive and physical impairments by clinical staff and were set realistic functional goals. Considerations were made for each participant's limitations in strength, passive and active range of motion, motor control, force modulation, cardiovascular ability and sensation. Based on this examination, custom routines matching the games taxonomy with the participant's functional goals were prescribed. The intervention facilitated a minimum of five hundred minutes of practice using the video game consoles and was supervised by health science undergraduates or physiotherapy trainees. Reinthal et al. [99] reported significant improvements in the Fugl-Meyer and Wolf Motor Function Test for the upper extremities.

18.6 Conclusions and Future Work

In this book chapter we have presented the state of the art in the use of video games for upper limb stroke rehabilitation. In doing so, we have provided an overview of applications in the field of robotics and virtual reality with a focus on evidence for clinically significant motor gains and potential for enhancing access and compliance to therapy. We have also introduced a number of potential issues associated with each modality of rehabilitation video games. In the section 'Video Game Design in Upper Limb Stroke Research' we identified key principles that are relevant to the development of targeted video games for stroke rehabilitation. Feedback and challenge were outlined as two primary constructs that are of great importance when designing software to enhance the practice of motor control in stroke populations. Furthermore, the application of sensorimotor theory into game design was discussed with reference to recent advances in the understanding of the mirror neuron system and approaches to bilateral training.

Although the devices in this chapter have in common the need for promoting higher volumes of motor practice with a focus on improving access and compliance, the types of technology used vary greatly. The use of robotic devices have shown particular strength at providing therapy for those more severely impaired [79], for both the proximal upper arm muscles [58, 110] and distal muscles in the hand [80]. Robotics also show promise as a method of improving the amount of therapy delivered without the need of a fully trained occupation or physiotherapist present. This aids in improving access to therapy as a patient is not restricted to one-to-one therapist guided sessions. However, in comparison to virtual reality applications, the cost of robotic devices is high and poses some issues with safety. Virtual reality and custom upper limb games are a lower cost alternative that has reported success in stroke populations [106]. These devices integrate a variety of different gaming activities with a focus challenge and feedback. Validation of off-the-shelf devices have mainly focused, so far at least, on the Playstation II EyeToy and the Nintendo Wii. Gameplay featured in these systems, and the games used within studies, is rudimentary and/or slower-paced than modern games. Interestingly, there has been little literature looking at the use of more recent commercially available technologies such as the Xbox Kinect and the Playstation 3. This may be due to more complex gameplay associated with newer gaming technologies that may not be suitable for elderly participants. Recent titles such as Kinect Adventures! require full body interaction and higher levels of motor control to complete game objectives. At the time of writing, the new Xbox One and Playstation 4 consoles are both released. Both consoles have placed emphasis on next generation motion capture devices being an integral part of the hardware involved. This should present an exciting opportunity for the field of off-the-shelf video games in stroke rehabilitation. However, given the lack of accessibility in game design of more recent technologies, it begs the question; will the games for these consoles be playable by stroke survivors? Finally, we introduced two studies that have expanded our knowledge of how off-the-shelf devices can be used within a rehabilitation context by developing protocols that use the devices as rehabilitation tools as opposed to purely therapeutic activities. Mouawad et al. [82], and, more recently, Thompson-Butel [118] reported success integrating a protocol based on Constraint Induced Movement Therapy that combines both clinic and home-based practice for a range of severity of impairments with clinical success.

In conclusion, the area of video games in upper limb stroke rehabilitation shows promise as a method of ameliorating upper limb impairments; creating a more enjoyable and accessible avenue for motor practice. This area is still in its (relative) infancy and currently lacks the depth of robust scientific evidence to adequately identify how effective this approach may be in comparison to conventional methods.

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Chapter 19
The Use of Qualitative Design Methods in the Design, Development and Evaluation of Virtual Technologies for Healthcare: Stroke Case Study

David Loudon, Anne Taylor and Alastair S. Macdonald

Abstract The development of VR technology for healthcare requires not only technical development but an understanding of the context in which the technology will be used, the people involved, and the environment, practices and processes in which it will be placed. In this chapter, the authors describe insights gained on this subject from the evolution of visualisation software for stroke rehabilitation through a series of RCUK-funded projects. The chapter discusses the value of qualitative design methods in engaging with users to both inform the technical development process and evaluate its outcomes, how they can be effectively integrated and the particular practical challenges involved in applying this approach in healthcare. The argument is made for using a methodology which endeavours to understand how to design and evaluate healthcare interventions which meet the needs of the current healthcare context and all its users and stakeholders, and which acknowledges that successful rehabilitation involves social processes that can be difficult to explore using quantitative methods alone.

19.1 Introduction: The Role of Design Methods in Delivering Patient-Centred Innovation

The importance of mobilising lay knowledge and experience is increasingly recognised as a driver of innovation in organisations. "In the 21st century, the big gains will come from professionals mobilising a far larger body of lay knowledge among users. Organisations that can mobilise the intelligence, investment and imagination of their users will reap huge gains in cost, productivity, flexibility and innovation" [4].

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Bate and Robert [2] in their work on 'experience-based design' within healthcare, describe this type of approach as a shift, "… from 'leader as client' to 'lead user as client'… the notion of the 'client user'. "This recent pre-occupation in design practice and research has extended the understanding of design from a practice comprising activities which were once purely those of the 'professional' (e.g., industrial) designer supplying a 'solution' to a problem, to an 'open innovation' approach where "it becomes important to acknowledge the part that end users and other stakeholders play… as 'co-designers', and where design is seen as a 'distributed social accomplishment' " [11]. This shift can only occur if the insights and experiences from end-users can be mobilised and 'exploited' effectively.

Savory [21] sets out a series of four ideal strategies for incorporating patient and public involvement (PPI) in the wider process of translative healthcare research involving technological innovation. He states that:

> "… PPI in translative research is analogous to the role of customers and technology users in other disciplines where technological innovation is a major focus…" and "… that within the open innovation paradigm the role of users and customers is central to the development of innovations. In turn, within translative healthcare research, there is great benefit in ensuring that the 'voice' of patients and the public is represented in all stages of the healthcare research cycle."

Using these strategies, Savory differentiates a spectrum (A to D) of PPI strategies, ranging from those which are concerned solely with "collecting patient data" (Strategy A) to those forms of PPI which are "patient-led", creating a "different dynamic" (Strategy B) and "where the mode of patient involvement is complex with them being involved in the design, conduct and even analysis of the research" (Strategy C), to a wider public involvement and education (Strategy D).

In this chapter three projects are described, which chart three key phases in the development of visualisation software to communicate data on movement difficulties. In the progression of the three phases, the use of design methods has evolved to include elements of the full spectrum, A to D, of the strategies described by Savory. The main focus of the chapter is on the third phase, which describes the design, development and evaluation of the visualisation method as part of stroke rehabilitation. The challenges are described for the integration of PPI strategies alongside more traditional quantitative clinical research methods and how these may redefine the traditionally passive role of the patient in their relationship with therapists.

19.2 The Healthcare Context: The Potential Value of Biomechanical Analysis for Stroke Rehabilitation

In this section, the healthcare context for the research is described to provide the rationale and background to the work, and to highlight the issues which are being addressed by the authors' design research approach.

The visualisation software was developed in response to enduring difficulties in the presentation and communication of biomechanical data on human movement for application in other fields. In this section, the current limiting factors for the use of biomechanical analysis in healthcare are described. The potential benefits of using visualisation to widen the use of biomechanical analysis for stroke rehabilitation are then discussed.

19.2.1 The Current Use of Biomechanics in Healthcare

The field of biomechanics, over almost 40 years of research, has contributed knowledge about the musculoskeletal system and the way it operates dynamically in relation to muscle force and the effects of gravity. In the context of healthcare therefore, biomechanical analysis can be used to scientifically assess the causes of the movement problems of patients and to measure their progress and outcomes following treatment. The biomechanical analysis systems currently available provide highly accurate 3D motion and force capture, and use dedicated software to generate the kinematic and kinetic parameters of the movement.

However, to date biomechanical data measurement and analysis are only used in a small number of clinical scenarios, largely in clinical gait analysis. These are specialist sessions which are expensive both in terms of the equipment and the specialist staff required to collect and interpret the results. Due to the expense of these sessions, they are only used with those groups of patients who have the most complex movement difficulties, for example children affected by cerebral palsy [14].

During gait analysis sessions the patient is asked to walk up and down the laboratory a number of times in the field of view of the motion capture equipment, and across force plates embedded in the floor. Several video cameras are also typically placed around the room in order to record the patient's movement from different viewpoints.

Once the patient has left the session, the data is subsequently processed and the three-dimensional kinematic and kinetic data typically represented as a series of two-dimensional graphs of particular measures relating to the movement in order to diagnose the cause of the impaired gait [16]. The graphs are used in conjunction with video data, clinical measurements and patient history to make a decision on the approach needed. The outcomes from these sessions can range from determining the rehabilitation required, prescribing of an orthosis, to recommendations for surgery [9]. However, this process is passive to the patient whereby the biomechanist and/or clinician will inform the patient of their clinical decision based on the objective data collected.

Therefore, there are a number of limitations to this model of applying biomechanics which make it unsuitable for general clinical use. The process is tightly integrated with expensive laboratory equipment limiting its use to only a small number of specialist hospital facilities and patient groups. This means that the majority of therapists in the UK do not have access to motion analysis equipment [24]. In any case, most therapists do not have training in biomechanics to the level required to collect motion analysis data and then use the software to perform an analysis.

Interpretation of the data collected by motion analysis, particularly with clinical gait data, is also considered to be problematic [1, 5]. The representations of biomechanical analyses as a series of 2D graphs is of limited use when trying to communicate to those without a background in biomechanics—with other health professionals or the patient themselves [22]. Additionally, these graphs do not provide a simultaneous view of the system of body segment movements in a dynamic context.

19.2.2 Widening the Use of Biomechanics: The Potential Use of Visualisation Software in Stroke Rehabilitation

The widespread use of motion analysis in stroke rehabilitation at present is not feasible due to the limitations as described above. As a consequence, clinicians must rely on other tools to assess the conditions of patients and provide rehabilitation. This section provides an overview of the impact of stroke on the individual and describes current approaches in stroke rehabilitation therapy in the areas of assessment, communication, and progress measurement. For each of these areas a description of the potential benefits of visualisation of biomechanical data is presented.

There are approximately 111,000 first time strokes in the UK every year with around 13,000 stroke victims in Scotland [3]. The incidence of stroke in males aged 75 years and older is increasing with a 4 % increase noted from 1994–2006 [3]. Young stroke survivors (45–65 years) represent between one quarter to one fifth of the total stroke population [6].

Stroke is a profound and life changing event where the individual and their family enter a process of change and adaptation with rehabilitation central to that process. However, recovery from stroke can be long and slow with physical recovery more evident in the first six months [12] and psychological recovery taking many months longer [7, 8]. Due to the unique and complex issues presented by stroke survivors [10] there is a need to gain an in-depth understanding of the issues they experience and to develop interventions based on those experiences that can improve overall outcomes for this patient population [20].

Feedback during rehabilitation sessions plays a central role for the retraining of skills acquisition for the individual. There are two main types of feedback: task-intrinsic and extrinsic (augmented). Task intrinsic feedback is the sensory-perceptual information naturally available to the individual whilst performing a task (visual, tactile, proprioceptive) whereas extrinsic feedback is information provided externally on the performance of the task by the individual (visually, using a mirror). In many cases intrinsic feedback post stroke is impaired due to the insult of the stroke on cognition, speech and understanding. This means that therapists often use augmented feedback (extrinsic) over the course of the patient's rehabilitation trajectory to communicate the appropriate feedback to stroke patients on their physical and functional recovery [23].

19.2.2.1 Assessment

The simplest approach available to the therapist is observation or 'eye-balling'. This relies heavily on the experience and tacit knowledge of the therapist, and is prone to inaccuracies and missed observations due to the subjective nature of this method. The advantage of biomechanical analysis over this method is that it can provide objective, accurate data on human movement beyond the immediately observable. The aim was to use visualisation to overcome the current limited use of this data by enabling non-specialists to access and understand the data, to enable their more widespread use.

19.2.2.2 Therapy and Communication

In current stroke rehabilitation, patients continue to have their functional problems and exercises explained to them verbally or using methods such as mirrors, or sometimes through video. However, self-image issues can mean that the individual can be distracted by their appearance. Further, cognition of the mirror image can be a difficulty within a complicated visual field where movement can be obscured by clothing or the clinical background [23]. These methods can prove challenging for the therapist to communicate the task specific information required at that time to allow for understanding and progress to occur.

The hypothesis for the visualisation software was that the display of objective movement data using a simple anonymised figure could enhance understanding and communication of the movement difficulties of the patient without distractions. Further, the ability to show overlays of calculated data could be used to show details of any compensatory movements, and provide a visual aid to communication between the therapist and the patient.

19.2.2.3 Progress

Currently quantitative measures e.g. step length, step symmetry and walking speed in lower limb, or the use of peg tests in upper limb, are used at baseline to assess patients' functional ability and may be repeated at a later stage in the rehabilitation trajectory. However, these tests are completed infrequently and documentation of each rehabilitation session is not consistent across all therapy staff, leaving a lack of a coherent measurement to assess and monitor progress.

By using visualisation software, the data from each motion capture can be easily stored to recall at a later date for comparison and analysis. This could potentially be used to provide a new resource for patients and therapists to track and monitor progress through rehabilitation—as a motivational aid and as a means to gauge whether the treatment is effective.

19.3 Evolution of Visualisation of Biomechanical Data Through Design Methods: Phases 1 and 2

This section describes the initial development of the approach to the visualisation software over two RCUK projects. Although originally not intended to be directly applied to healthcare, these two projects illustrate the origins and context of the approach to the visualisation of biomechanical data, and also the key role of design methods in questioning the prevailing assumptions of the role of biomechanical analysis. For each project, the aims, process, visualisations produced and qualitative findings are described.

19.3.1 Phase 1: The Prototype Visualisation Tool

19.3.1.1 Intention

The aim of the first study was to produce a software tool to enable designers to consider the effects of reduced muscle strength due to the ageing process [18].

19.3.1.2 Process

In this study, dynamic 3D movement data were captured from 84 older adults in the 60+, 70+ and 80+ year-old categories, using an optical motion capture system, maximum strength measurements, and reaction force data measured using floor mounted measurement platforms. Data were collected in the laboratory during 11 functional mobility tasks which mimicked activities of daily living as they would be performed in the home. The focus of the kinetic data collection was on the lower limb, as risk of falls was identified as a major factor in everyday mobility tasks in this population.

The model for the overall project was a traditional scientific process, with the involvement of the patient conforming to Savory's Strategy A (Fig. 19.1):

- Older adults were the subjects of the research, to be measured.
- The expert engineer analysed the data and produced the results.
- The results were to be presented in a format for designers.

The visualisations were designed:

- By prototyping different ways of displaying the data.

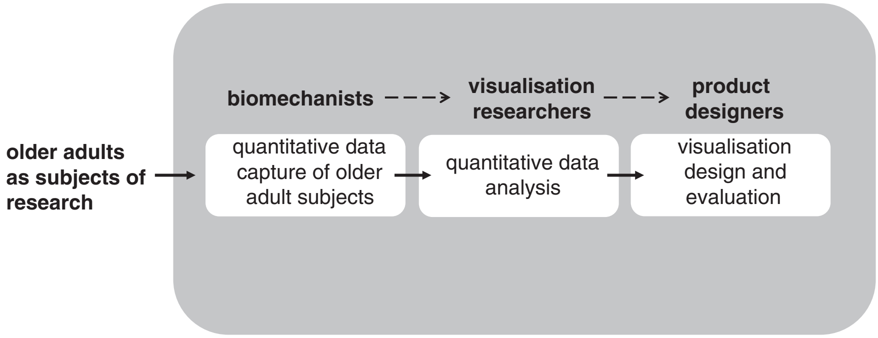


Fig. 19.1 Data-centric approach to visualising biomechanical data. The older adults had no active role other than participating as subjects from whom data was acquired. This data was acquired and analysed by biomechanists: the visualisation researchers used the results of the analysis as a basis for their visualisations for the designers

- Through a review of the literature to understand the requirements of the product design process.
- By being informed through interviews with product designers.

19.3.1.3 Approach to the Visualisations

The approach adopted to visualising the data was to minimise the viewer's exposure to the complexity of the data and the underlying calculations and to use the movement data to provide the context for the kinetic data.

Although the calculation of the demands of the task required the knowledge of the biomechanical moments, direction of forces and joint angles, the end result could be expressed as a ratio. The term 'functional demand' was chosen for this percentage value, i.e. how hard the muscles are working relative to their maximum capability.

Visualisation software was developed to allow observation of the kinematics of the movement, using a 3D mannequin, with the functional demand value represented visually at each of the joints (using a continuous colour gradient from green at 0 %, amber at 50 %, through to red at 100 %). Mapping the data in this way enabled the relationship to be highlighted between the mobility tasks and the dynamically changing functional demand at each of the joints.

19.3.1.4 Qualitative Design and Evaluation Findings

The initial idea was that the data would be presented to designers visually, integrated with CAD software. The hypothesis here was that this mode of

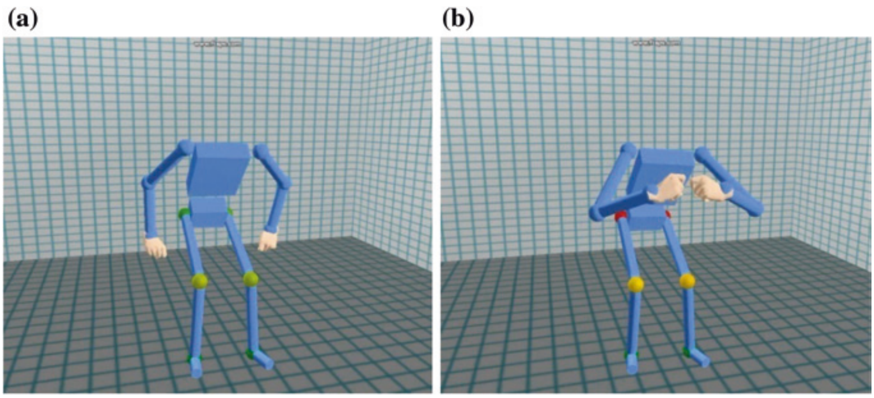


Fig. 19.2 Snaphot of dynamic visualisation of the functional demands of the sit-stand task for one of the older adult participants **a** with the use of arm-rests—the spheres at the hip are *green*, and at the knee a *yellow-green*, indicating low functional demand for this individual. **b** Without the use of arm-rests—the spheres at the hip are *red*, and at the knees *yellow/orange*, highlighting that the movement is more demanding on the lower limbs, and is close to this individual's maximum capability in their muscles around the hip joint during the movement. This shows the importance of arm rests for this older adult participant

visualisation could enable complex biomechanical data to be understood by designers, and suitable for use within the design process, e.g., on understanding the importance and effect of designing a chair with arms to encourage the use of upper limbs to reduce demand on lower limb and hip joints (Fig. 19.2).

The visualisations allowed for the viewer not only to access the 'data' but also to see the relationships between the demands of the task and the movement of the individual. It was possible to visually compare the same individual doing the task in different ways. Further, it was possible to compare different individuals doing the same task and to examine the functional demands on different individuals with different functional limitations [e.g. arthritis at the hip, back pain or knee replacement (Fig. 19.4)].

The power of the visualisation method to make the data accessible to non-biomechanists was indicated in a feedback session with older adults who had participated in the laboratory measurements for the research (ca. 40 older adults attended the event). The comments and questions from the audience were about how the visualisations of the data related to their own experience—something not possible with conventional biomechanical data representation.

Subsequent interviews (a mixture of individual interviews and small group interviews) with older adults (N = 3), biomechanists (N = 2), healthcare and rehabilitation professionals (N = 5), product designers and human factors consultants (N = 7) were held to investigate this potential further. An important finding at this stage was that each of the stakeholder disciplines could sensibly comment on the data, proving the value of the visualisation method. It was also clear that the nature of the discussions varied from each of the different stakeholders involved, and how the different issues and experiences raised highlighted their varied backgrounds and disciplines. The depth of understanding and interpretation of the data could also be contrasted. Interestingly, the designers—the original audience of the research—described the data at a more superficial level, yet the therapists interviewed were able to describe the details of the movement and even propose underlying medical conditions of the individual. This highlighted the need for support for not only the *presentation* of the data but the need to *support the interpretation of the data* based on the knowledge of experts in the relevant area. To investigate these findings further, a structured evaluation study was proposed, as described in the following section—Phase 2.

19.3.2 Phase 2: Evaluating the Potential of the Visualisation Method with People

19.3.2.1 Intention

The second study aimed to explore the emerging potential of the use of visualisation to enable different disciplines to access and understand complex biomechanical data. Further, the aim was to explore the potential this could provide for sharing expertise and experiences relating to the data between stakeholders—older people, and the range of professionals concerned with the design of their healthcare and built environment [16].

19.3.2.2 Process

The prototype visualisation tool was evaluated through a qualitative methodology employing interviews and focus groups (Table 19.1). Older adults were selected to match as closely as possible the age cohort of individuals (and their associated age- and health-related conditions) from whom the original data for the Phase 1 visualisations were obtained. The range of professions selected comprised clinical medicine, physiotherapy, occupational therapy, bioengineering, disability consultancy, engineering design, and interior design. The professionals selected combined practitioners who had close experience of working directly with end-users of healthcare or design.

In contrast to the first project (Fig. 19.1), the different stakeholder participants were given an equal level of importance in the investigation (Fig. 19.3), conforming to Savory's Strategy B.

19.3.2.3 Approach to the Visualisations

The full dataset from the Phase 1 project was processed for visualisation (only a subset of the data were processed in Phase 1) in order to examine and select those

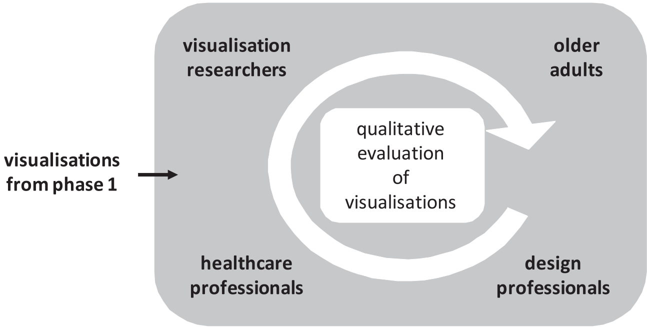


Fig. 19.3 The views of a range of stakeholder groups concerned with older adult mobility were represented equally in Phase 2. Older adults who were previously regarded as 'subjects' of the research are active participants in the research

Table 19.1 Participants in qualitative Phase 2 study

Qualitative method	Cohorts and numbers
Interviews	Older adults (n = 18)
	Healthcare and design professionals (n = 15)
Focus groups (FGs)	FG1: older adults (N = 8)
	FG2: healthcare and design professionals (N = 8)
	FG3: older adults and healthcare and design professionals (N = 8)

visualisations which would demonstrate a range of functional limitations for discussion. The visualisation software was updated to enable filtering of the dataset by age, gender, and health conditions in order to explore the full dataset in more depth.

From this process, a number of visualisations were selected which could be used to discuss particular issues in the focus groups, e.g. the same individual performing a task in two different ways (Fig. 19.2), or a comparison between different individuals performing the same task (Fig. 19.4).

19.3.2.4 Qualitative Feedback/Findings

The focus groups explored the value of, and potential uses for, the visualisation approach in communicating biomechanical concepts and data. The findings [17] showed that each of the participant groups could interpret the visualisations of biomechanical data in a way which enabled them to describe what they were seeing and relate it to the context of their own experience, e.g. the older adult describing an activity of daily living, the healthcare professional diagnosing a movement problem or the designer attempting to reduce the physical demands on the user. This sort of discussion of biomechanical data with the different stakeholder groups was unique and would not have been possible with the biomechanical data in its original representation.

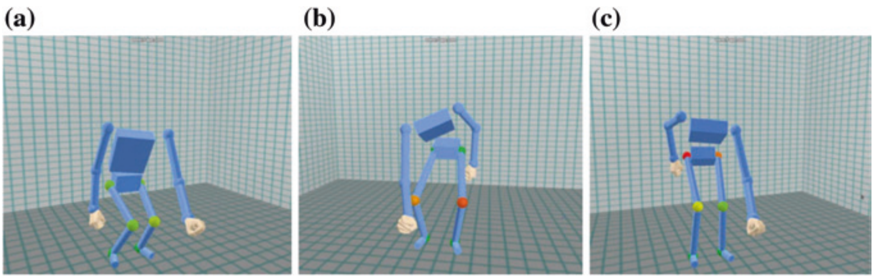


Fig. 19.4 Comparison of three different individuals lifting an object from a high to a low shelf: (*left*) 74 year old female with no apparent problems—the spheres at the knees and hips are *green* indicating low demand; (*middle*) 81 year old male, osteoarthritis of knees—the hips joints are *green*, but the left knee is *red* and the right knee *orange-red*, showing their lack of strength around the knee joint is making this task demanding for the individual; and (*right*) 67 year old male, history of back problems and history of fractures—the knee joints are yellow-green, but the right hip joint is *red*, and the left hip joint *orange-red* indicating the high demands of the task for this individual [16]

The older people in the study were able to participate in, and contribute to, discussions about the design of their healthcare and of their built environment with professionals in the respective fields:

> **Older adult 1**: "I think the important thing to get across is, just like this, how valuable the handrail is…and it gives people confidence to go up stairs. Without a handrail you say 'oh god, am I going to get up here'. The handrail's very important."
> **Older adult 2**: "We spoke about going upstairs holding on to both [hand-rails]…but that's not possible if you're using a walking stick, you know, you've got to hold the walking stick in one hand, and just use one hand to go up." [16]

The visualisations enabled the range of professionals concerned with the health and wellbeing of older people to speak across their disciplines about the biomechanical data:

> **Design Engineer**: "One's moving a lot quicker than the other one. Me as a boy, me as I am now."
> **Designer**: "The person on the right looks less agile."
> **Design Engineer**: "They're bending in a very different motion."
> **Physiotherapist**: "The left one's going down much further. The actual height drop is considerably more on the left, and the leg pattern's symmetrical on the left and asymmetrical on the right."
> **Bioengineer**: "The left figure appears to be better balanced in comparison to the right."
> **Physiotherapist**: "I think the person on the right has to use a lot more trunk rotation in order to achieve what they're trying to achieve."
> **Design Engineer**: "He's having to turn in a different way. I guess the assumption is that he's got an imbalance somewhere in his joints, so he's got to do things differently if he's reaching with his left hand from the way he'd do them if he were reaching with his right hand. Which means one size doesn't fit all…one solution's not going to work for everybody. Or maybe not for the same person in two different positions."

Several possible healthcare applications were envisaged both by clients and healthcare professionals, and this led to the generation of a subsequent project (as described in Phase 3) where we could evaluate the potential benefits of using visualisation to allow an individual to see their own movement data in a healthcare setting and assess the impact that the visualisation technology had in rehabilitation practice.

19.4 Investigation of Visualisation Software in Stroke Rehabilitation Using Qualitative Design Methods: Phase 3

19.4.1 Intention

The potential benefits of the use of visualisation of biomechanical data in stroke rehabilitation were described in the first section. The aim of this Phase 3 study was to investigate this potential, and the feasibility and acceptability of the visualisation technology in rehabilitation, using a mixed quantitative and qualitative design and evaluation process.

Although consultations and focus groups, involving non-biomechanical professionals and lay older people, had been used during Phases 1 and 2 and opinions solicited on what was shown to these groups, there had been little input from potential end-users into the design of the visuals themselves.

Consequently, during Phase 3, an enhanced iterative and 'participative' approach was designed to engage the therapists and patients, as well as the trial leads, in the design of the visual tools from the outset of Phase 3, through the process (outlined in Table 19.2). The impact of this type of participative engagement and co-development process is evidenced by its influence on the visuals and the tools, as described in [15].

19.4.2 Process

In this project, five randomised controlled trials (RCT) were run in the context of different rehabilitation settings. For focus and clarity, only three of these trials are described here, all concerned with stroke rehabilitation: (1) lower limb rehabilitation; (2) upper limb rehabilitation; and (3) ankle foot orthosis (AFO) tuning.

Although an RCT offers a rigorous research method for determining whether or not a cause-effect relationship exists between a treatment and its outcomes, Lewin et al. [13] highlight the importance of integrating a qualitative process into quantitative trials: "Complex healthcare interventions involve social processes that can be difficult to explore using quantitative methods alone … Qualitative

Table 19.2 Overview of the methods used across the project to engage stakeholders during each of the key phases of the trials

Key phase	Method
Design	– Focus groups – Testing and feedback sessions with user groups
Pre-trials	– Patient interviews – Health professional interviews
Trials	– Observation – Video
Post-trial	– Patient interviews – Health professional interviews – Workshops with patients and health professionals

research can support the design of interventions and improve understanding of the mechanisms and effects of complex healthcare interventions". Based on this, qualitative methods were integrated into the trial design process to explore the feasibility and acceptability of the visualisations on the rehabilitation experience and the understanding and value of them across the rehabilitation process. Key areas explored were in communication, motivation and progress; areas derived from the stroke literature and discussion with experienced clinicians involved in rehabilitation care.

19.4.3 Approach to the Visualisations

Stroke can be a devastating and very emotional experience, often affecting understanding and motivation. In the development of the visual tools, both the patients' and therapists' agendas had to be articulated and embodied, and the further development and refinement of the visual tools enabled these agendas to be embodied simultaneously along with the clinical biomechanists'.

A range of motion capture technologies were used in the different trials to provide 3D movement data relevant to the rehabilitation setting [15]. Custom software was written to display the data as a virtual mannequin of the patient. This could be presented in real-time or played back after the movement as the rehabilitation task dictated.

Custom visualisation software for each stroke trial was created to present 3D visualisations of the patient's own motion capture data during the rehabilitation session with the therapist (Fig. 19.5).

19.4.4 Qualitative Feedback Process

In the design of the trials the authors, building on findings from previous work, proposed that a visual tool developed for and utilised in rehabilitation settings

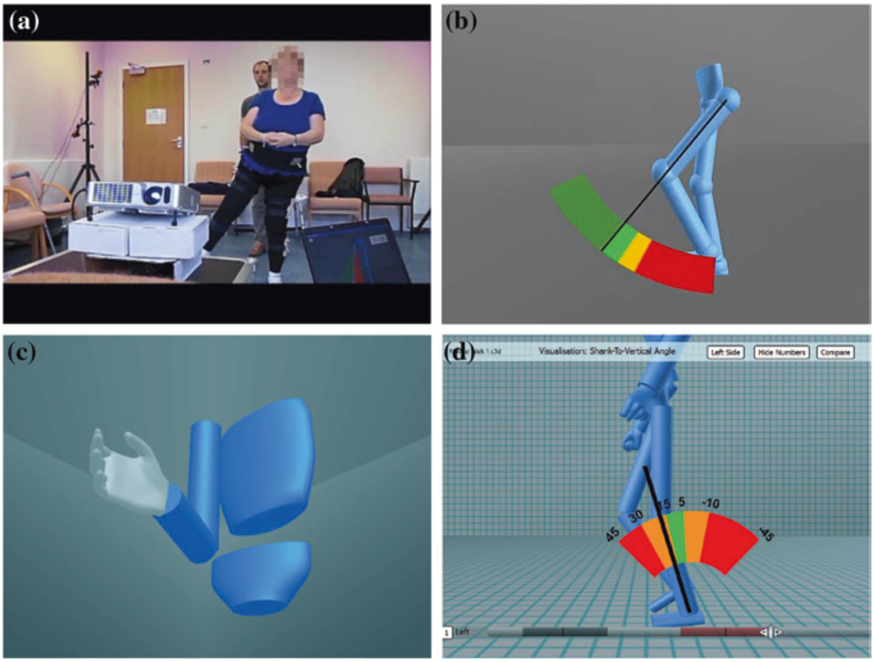


Fig. 19.5 **a** Patient using the visualisation software with a physiotherapist in clinical trials. **b** Knee lift exercise visualisation in lower limb rehabilitation following stroke. **c** Reach and grasp visualisation in upper limb rehabilitation following stroke. **d** Shank angle visualisation for Ankle Foot Orthosis tuning after stroke

could act to mediate and enhance the social discourse between the therapist and the patient as well as making appropriate biomechanical information available in formats that would be understandable to each.

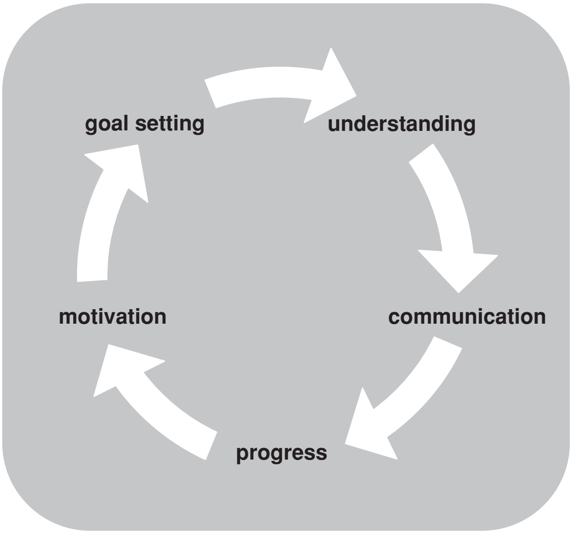
The qualitative feedback process began with preliminary pre-trial workshops, where it was found, through the use of this visual method, that stroke survivors were enabled and empowered, much more equably, to participate in the discussion of the problems and very human issues they experience such as, e.g., their understanding of the correct movements to perform, and issues affecting their motivation (influencing their progress and rate of recovery). For example:

> I was given exercises that I didn't understand why I was doing them. You need to be given an overview of why you need to do these exercises i.e. to get you up the stairs. The overview needs to be simple due to the cognitive challenges people suffer at this time. I think this [visual] would be very useful as people need to know and understand why they are doing them (Female Stroke Patient, aged 52)

> Really good when you put the footprints up made me realise what was happening really like it [visual] wish we had had it find it very motivating (Male Stroke Patient, aged 54)

> It [visuals] lets us see where we were and where we are now and it's good to monitor progress. After a stroke everybody is different, you have had a brain attack and everybody recovers differently. This would be a great aid as you can't see yourself walking (Male Stroke Patient, aged 58)

Fig. 19.6 Methodological framework



The importance of integrating a qualitative methodology across the whole of the trial process, involving the pre-trial workshops and interviews, observations and focus groups (Table 19.2), ensured that patients' and therapists' feedback was considered iteratively with regard to the design and future development of the visual method. This conforms to a mixture of Savory's Strategy B '*patient-led*' creating a '*different dynamic*' and Strategy C '*where the mode of patient involvement is complex with them being involved in the design, conduct and even analysis of the research*'.

This process enabled the design researchers to gain an understanding of the end-users' interpretations of and responses to the visualisations, to employ their many suggestions and ideas for improvement, and also to recognise some of the emotive issues triggered when viewing representations of themselves on screen.

19.4.5 The Methodological Framework

The framework evolved from early findings which indicated that there is a relationship between: (1) communication and understanding of correct movements; (2) motivation in the patient to complete a programme of rehabilitation; (3) understanding (in both patient and therapist) of progress at each stage of the rehabilitation programme; and (4) (for both the therapist and patient) goal-setting. Based on the framework (Fig. 19.6), key questions were developed and integrated by the authors into the data collection phases of the trial to allow for more detailed data to be collected on the potential for changing the dynamics of the rehabilitation session and patient outcomes through the use of the visualisation technology.

From the pre-trial interview data with a range of rehabilitation therapists (n = 17), early findings confirmed the cyclical process of the methodological framework in relation to the visualisation technology as many therapists discussed the inter-relatedness of the concepts of understanding, motivation and progress illustrated in the following quote:

> The visualisations may help patients understand their rehabilitation tasks more and allow them to become more involved in their sessions with more communication occurring between the therapist and patient. The visualisations would help promote interaction and communication leading to the patient, hopefully, taking ownership of their rehabilitation tasks leading to them progressing positively through the programme (Occupational Therapist 1)

The ability of the tool to visually communicate specific rehabilitation information received positive comment from both therapists and patients as it not only changed the way in which information was communicated but also the amount of information needing to be communicated:

> Just by the, the mere fact it's visual, you'll need less verbal explanation as to what you're trying to achieve, 'cause you could take them through that movement and show them it and then you could get them, you know to attempt whatever stage that you feel they're working at and they're watching that, and they'll have a very good understanding what they're trying to achieve, I think it'll be very motivational for patients (Occupational Therapist 2)

The ability of the visual technology to allow the therapist to communicate to the patient the movement to increase their understanding is illustrated in the following quote from one of the participants in the lower limb trial:

> It wis'nae just, you know the thing'wi' to start walking, it was just the pelvis, keeping it straight, it's only when you saw the visual feedback you could see, you knew where you'd went wrong But they [physio] never told me about my pelvis and all that. Because if they explained to me then I would have started off the walking bit like that. Although they've all told me, they all told me about my leg snapping back, you know to watch for the leg snapping back, they did tell me that bit but not about my pelvis and that you know I was doing a lot o' the snapping, em… but eh now I'm doing my best to try and stop that, and tae, a few times near the end o' the session trial therapist would say to me "there you done that walking, you didn't snap back once", and I says "I know I could feel that I didn't do it", I says (Female Stroke Patient, aged 54)

Thus, the tool appears to communicate the complexities of the rehabilitation task to patients in a real and meaningful way. This changes the current process and dynamics of rehabilitation potentially leading to a more motivated patient progressing through the rehabilitation process. It is interesting how the above participant had the ability to "feel" the position of her pelvis and to "know" that it was in the correct alignment through the use of the visual. This allows for the authors to propose that the visualisation method would better empower future stroke survivors resulting in a more equable relationship with their rehabilitation therapists.

In the future, the tool may not only change the "therapist to patient" relationship but also the "therapist to therapist" relationship through its ability to be used to objectively assess the competency or efficiency of the functional movement or task; an area currently subjective and found to be challenging:

> Having the ability to view the movement during the session will allow the therapist to measure the level of efficiency of the movement as currently this is a subjective measure (eye of the therapist). Currently there can be variations between therapists but by having the movement recorded; it provides an objective measure rather than the therapists needing to depend on the subjective clinical notes of the therapist (Occupational Therapist 1)

> It would probably be a good assessment tool, looking at it because you, you don't have kind of bits of clothing, you don't have other things distracting you, you can look specifically at the alignment and the movement of a limb and con., it just makes it so much clearer……so you can, if you're then using that as an assessment tool and you can then, again pick away at the, the little problems and try and sort them (Physio 1)

The multifaceted features of the tool provide the therapist with the capability to tailor the rehabilitation session and the types of information communicated during that session to the needs of the individual patient.

Adopting an iterative qualitative feedback approach to the process of data collection at key phases across the project (Table 19.2) allowed for the development of a detailed picture of the potential role and use of the visualisation of biomechanical data during rehabilitative healthcare with patients and practitioners over the course of a stroke survivor's rehabilitative pathway. Early findings would suggest that the visual method allows for improved patient understanding of their rehabilitation tasks, improved communication between patient and therapist, patient motivation and progress, previously perplexing challenges to successful rehabilitation. Through this visual method, clinicians can collect and analyse patterns of accumulated data to identify changes in the patient's condition over the course of their rehabilitation trajectory that could: i) aid and guide clinical decision-making about future treatments and management; ii) aid in the education of future students or clinical discussions of problematic/complex cases; and iii) teach carers how to work with their partner.

19.5 Discussion

What has been the impact of introducing qualitative design methods within this healthcare research context? Reflecting on the different phases it is useful to speculate on the role and nature of the visuals in Phase 3, i.e. their adoption in an RCT, if there had not been a progression in the approach to the research through the adoption and application of user-centred design methods between Phases 1, 2 and 3.

In the three phases of work presented in this chapter, three different models of interaction between the stakeholders and the visualisations of data evolved (Figs. 19.1, 19.3 and 19.8), influenced by Savory's PPI model. The authors now compare and contrast approaches to user engagement in this type of research.

Had a traditional `specialist-centric' and `quantitative data-centric' approach to developing visualisations been adopted, this would likely have followed a process such as illustrated in Fig. 19.7. In this approach, the technicalities of the analysis of the motion capture data and the ability to assess quantitative outcome measures by the biomechanist and therapist would be the dominant pre-occupations of the research design and outcomes. The focus would be on the design of the visualisations

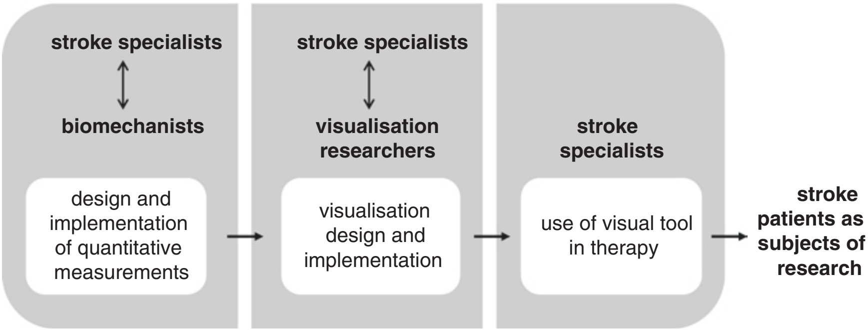


Fig. 19.7 Specialist-centric approach to a visualisation tool for stroke

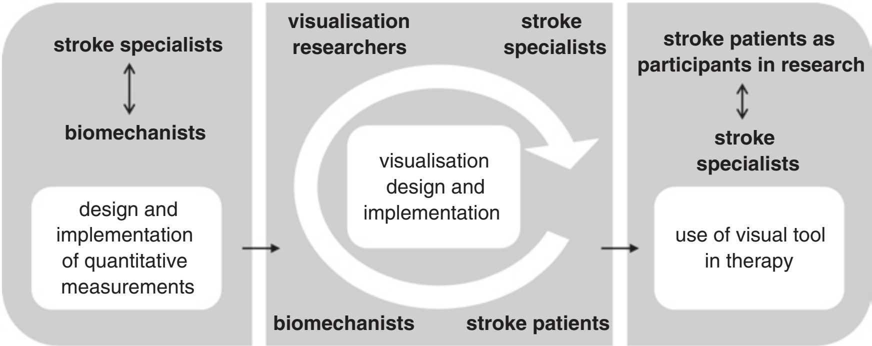


Fig. 19.8 Phase 3 model, as a result of progressively adopting Savory's PPI model

to better support the expert specialist to understand and analyse the quantitative data and to evaluate and measure the patients' problems on a purely functional basis. These would have then been communicated to the non-biomechanics specialist therapist and the patient in a prescriptive and objective manner.

While the above example is illustrative only, it is not an uncommon approach to the design of healthcare technology—indeed this is largely the approach taken in current clinical gait analysis. With this kind of approach, there is no intention to solicit input from relatively 'biomechanically-inexperienced' patients or rehabilitation therapists in what this data could mean to them and how this might help enhance the rehabilitation experience for the patient and the practice for the therapist. In this approach, the process of development of the technology would, therefore, reflect and reinforce the traditionally dominant role of the 'specialist as gatekeeper' to knowledge and of his/her view of how best to carry out the rehabilitation.

Contrasting this with the evolving approach described above in the three phases of the research, through consultation with key stakeholders throughout the process, the potential of the dynamic visualisation of biomechanical data as a means to empower the non-specialist with the information was explored. By Phase 3 the approach had evolved into an iterative process of co-development and co-design which ensured that the qualitative feedback data influenced the technical development and specification of the visualisation software and tools, reversing traditional approaches (Fig. 19.8). This helped ensure that the patients' and therapists' agendas and issues were also prioritised, and considered as crucial as those of the biomechanist or clinician. It also helped ensure that everyone was 'on the same page', flattened traditional 'top-down' agendas and decision-making, allowing input from everyone involved in the process of both delivering and benefiting from using the visuals during the rehabilitation process.

19.6 Conclusions

In complex interventions such as that described for the RCTs in Phase 3, approaches to prospective solutions developed by a single discipline may be less successful in acknowledging the complexity and 'multiple confounders' [19] of a situation than those approaches embodying the collective experiences, insights and expertise of all involved. Our work has revealed that rehabilitation involves social processes that can be difficult to explore using quantitative methods alone and that developing visual tools and VR technologies for successful rehabilitation will benefit from acknowledging, reflecting and embodying the different requirements of all involved in the delivery and use of the intervention or therapy. This can be achieved through a participative and co-design process to mobilise the intelligence, experience and imagination of their end-users in their development.

Acknowledgements Phase 1: 'InclusiveCAD', Integration of biomechanical and psychological parameters of functional performance of older adults into a new CAD package for inclusive design. EPSRC/EQUAL, 2002–2005 (GR/R26856/01). University of Strathclyde, The Glasgow School of Art and Queen Margaret University College.

Phase 2: 'Envision', Innovation in envisioning dynamic biomechanical data to inform healthcare and design guidelines and strategy', ESRC New Dynamics of Ageing (NDA), 2007–2009 (RES-352-25-0005). The Glasgow School of Art and the University of Strathclyde.

Phase 3: 'Envisage', Promoting physical independence by involving users in rehabilitation through dynamic visualisation of biomechanical data. MRC Lifelong Health and Wellbeing programme (LLHW), 2010–2013 (G0900583). LLHW is a cross council initiative in partnership with the UK health departments and led by the MRC. University of Strathclyde, The Glasgow School of Art and Glasgow Caledonian University.

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Chapter 20
Toward an Automatic System for Training Balance Control Over Different Types of Soil

Bob-Antoine J. Menelas and Martin J. D. Otis

Abstract It is known that the type of the soil can affect balance. Here we report an automatic system having: a serious game, a physical setup and an intelligent clothe designed for training users at maintaining balance over five types of soil (broken stone, stone dust, sand, concrete and wood). By using an augmented shoe and proposed navigation metaphor, in this game, the user is invited to browse a maze while standing balance over the physical grounds. During the exploration, exercises that target assessment of balance control are suggested. To insure the effectiveness of this training program, as a first step, we have tested the proposed system with six healthy persons. Results indicate that the system can detect how the type of soil affects users balance. This opens a new avenue for more ecological, automatic and low cost personal rehabilitation systems.

20.1 Introduction

Falls represent a major factor in the frail elderly. In developed countries, we observed that nearly half of falls among elderly caused minor injuries while 5–25 % sustained serious damages such as fracture of the proximal femur [9]. Beyond the physical injuries, in many cases, falls leave a psychological impact due to the fear of falling. As a consequence, even without an injury, a fall can cause a

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loss in confidence and a reduction of mobility. This can lead to a decline in health and function, hence can contribute to future falls with more serious outcomes [5]. These observations have promoted the development of multiple programs dedicated to prevention of accidental falls. Given the multifactorial aspect of falls, these programs have to target several factors that can constitute a certain risk of falling [3]. In this way, several programs have coupled the practice of physical exercises to analysis of balance and gait. Others have been focused on control of vision, hearing and blood pressure. Our research project aims at taking all these factors and even several others into account. Here, we consider training balance control via exercise programs.

Balance control via exercises has been an active research topic in the last decade, multiple approaches have been proposed. However, to the best of our knowledge, no research has yet integrated the type of soil in training programs targeting improvement of balance control. Given that the type of soil that a person walks on, may affect his balance [19], our work aims at helping users at maintaining their balance over several types of soil through the use of a serious game.

By playing this game, we want to bring the user to experiment balance control over several types of soil: broken stone, stone dust, sand, concrete and wood. To insure the ecological validity of the system, it combines elements of the real world to an interactive virtual environment. The game is designed in order to be usable for the realization of home exercises. In the proposed game, the user is invited to browse a virtual maze having five types of ground (see Fig. 20.1). During the exploration, fitted with an augmented shoe, the user has to face several distracting stimuli designed in order to bring him at realizing movements similar to those that occur at the beginning of a spontaneous loss of balance. Delivered stimuli are based on exercises targeting balance assessment (Berg Balance Scale and the Tinetti Balance Assessment Tool). During this process, various measures relative to the user's posture and its heart rate are measured in order to check how the situation affects the user.

The chapter is organized as follows: related work is presented at Sect. 20.2, the developed serious game is detailed in Sect. 20.3, an initial experiment of the system is discussed in Sect. 20.4. Section 20.5 concludes the chapter.

20.2 Related Work

Various studies have proved that balance control plays an important role in fall prevention. As a result, it has been incorporated into multiple programs aiming at fall prevention. Previous researches show that practice of exercises can reduce the risk of fractures. By helping to maintain bone mass, it allows to improve notably the stability posture. Madureira et al. [18] have shown that balance training program is effective in reducing the risk of falling in elderly. Traditionally exercise programs were delivered in a class situation or individually by professional physical therapist [20, 24]. To alleviate several constraints regarding such an approach (cost of transportation, schedule management, etc.) new methods that use some

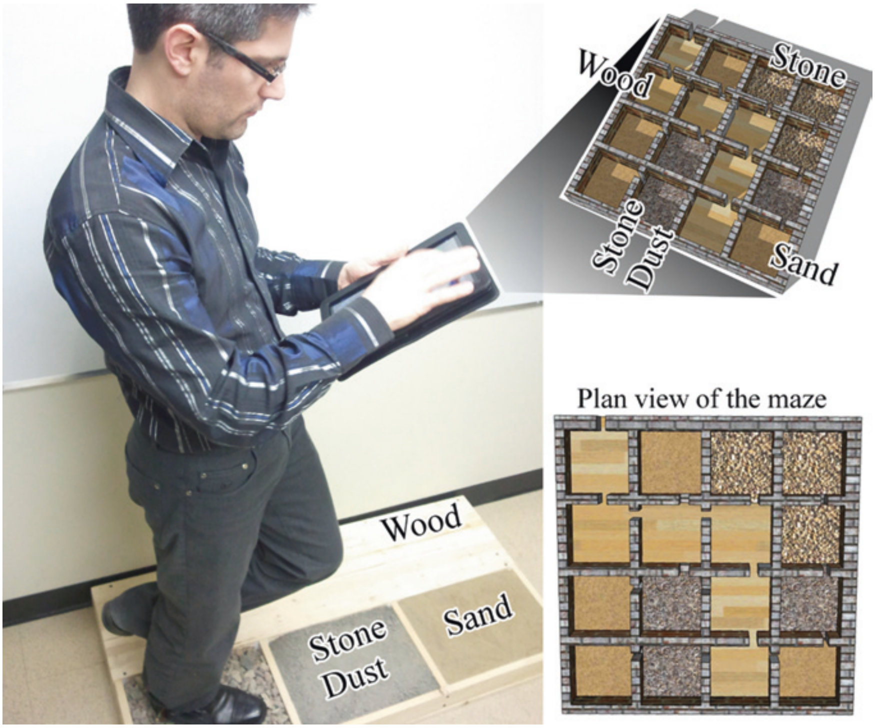

Fig. 20.1 A user is playing the game while standing on one leg

technological devices have emerged. Exploited approaches range from pure visual system (like the Nintendo Wii Balance Board) to vibrotactile feedbacks embedded in a cell phone [7, 10, 15]. In [7], a six-week home-based balance training program using Nintendo Wii Fit and Balance Board is presented. In the same way, Grosjean et al. [10] have combined the Nintendo Wii Fit platform to traditional physical therapy interventions. Also, Lee et al. [15] have described a cell phone based vibrotactile feedbacks system dedicated to balance rehabilitation training. Realized experiment shows that real-time feedbacks provided via a cell phone can be used to reduce body sway. Recently Brassard et al. have used an instrumented shoe in order to develop an automatic version of the well known *Berg Balance Scale* [1]. In the same wat Gagnon et al. [8] have used a serious game for the learning of vibrotactile feedbacks presented under the foot .

Looking at the literature, we observed that physical characteristics of the soil have not been considered for training of balance control. For person with gait disorder or losing autonomy, it appears that walking on different type of soil could be a challenge and may represent a risk of falling. Moreover, it has been demonstrated that the type of soil may affect the gait [19]. As result, it seems quite important to help users at maintaining their balance over different types of soil. Considering the promising results of cited studies, we have developed an interactive game for balance training over different types of soil.

The proposed game combines elements of the real world to an interactive virtual maze. By exposing the user to various destabilizing events (perturbations) the game aims at helping users strengthen their lower limbs while learning facing perturbations that can occur in daily activities. Moreover, by using an interactive shoe, the dynamic of the users and his ability to maintaining postural stability after a perturbation are logged in real time. In the following, we describe the game.

20.3 Proposed Game

With this game, we want to design an environment that can help users at training their balance over several types of soil. Given that successful previous balance training programs have usually run over a long period [18], we designed the game in a way so that a user can experiment it over a long period. Among several other requirements, it has been designed to be fun, interactive, safe, ease to use, usable at home and low cost.

In this game, the player is invited to browse a virtual maze as fast as possible while standing balanced on a specific type of soil. To do so, fitted with an augmented shoe, to move in the maze and to perform exercises, the player remains physically at the same position and uses the metaphor presented at Sect. 20.3.1.1.

20.3.1 Apparatus

The game requires a physical setup and an instrumented shoe. This section briefly summarizes these two components.

20.3.1.1 Interactive Shoe

Recently, we have developed an intelligent system that aims at prevent accidental falls related to conditions of the physical environment of the person (slippery ground, steep slope, etc.), or abnormalities of its gait. This system is centered on an augmented shoe (right part of Fig. 20.2). This device counts, on one side, a set of sensors that serves for characterizing the dynamics of walking, the posture of the user and the physical properties of the environment. For example, they measure the velocity and acceleration of the foot, bending of the sole and forces applied at five points under the foot (as seen in Fig. 20.5). All these sensors are exploited to compute the risk level associated to physical characteristics of the environment. On the other hand, this device brings together several actuators aiming to transmit vibrotactile signals to the user. These signals intend to attract the attention of the user towards situations deemed dangerous by the control system running on a *Android* device (tablet or smartphone). For more details regarding the interactive shoe, one can refer to [23, 25, 26].

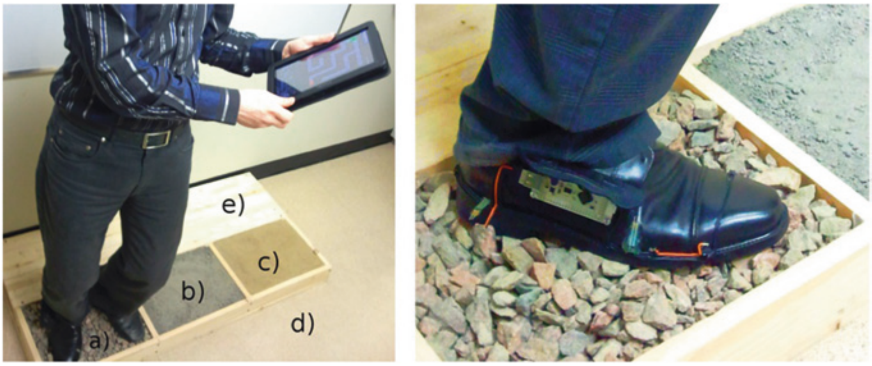

Fig. 20.2 Setup used for training of balance control (*left side*). Interactive shoe (*right side*)

As part of this game, for each soil type, we used these sensors to measure the variation of several parameters (acceleration, sole bending, applied force by the user, etc.) when maintaining or recovering balance.

Another sensor used in the system is a portable wireless device that helps to measure the electric activity of the heart. This heart rate monitor is designed for cardiovascular training running, jogging, or any kind of strenuous exercise. Its main component is a heart rate monitor strapped over the chest with Bluetooth capabilities. This device reads and transmits the heart rate to the *Android* device. This device has been described in [25, 26].

20.3.1.2 Physical Materials

Our work intends to fulfill the gap observed in the literature about balance training over different types of soil. To ensure the ecological validity of this work, even though we propose a serious game, we wanted to use physical soils. Moreover, in order to cover a wide range of soil, three granular (deformable) and two non-deformable materials were used as type of ground. The three granular materials are broken stone, sand and dust stone whereas concrete and wood were the non deformable. These materials have been selected because of their rheological characteristics and their relatively high rate of use in living environments. In the context of the game, they spread out in a tray as shown in Fig. 20.2.

20.3.2 Metaphors Used for the Displacement in the Game

In the proposed game, the user has to browse, as fast as possible, a virtual maze while standing balanced. Since the goal behind the game is to improve balance control over different types of soil; it seems appropriate to exploit body

Fig. 20.3 Possible setup of a shoe-mounted accelerometer

Fig. 20.4 Gestures used for the accelerometer based metaphor. **a** Forward. **b** Backward. **c** Rightward. **d** Leftward

interactions for displacements in the maze. Moreover, it has been showed that such interactions may enhance the engagement of users in the games [2].

For this, interfaces such a *Microsoft Kinect*^{TM}could be considered. Indeed, a recent study used the *Microsoft Kinect*^{TM} to assess kinematic strategies of postural control [4]. However, such a system does not really fit our need since it cannot be used to evaluate all aspects regarding the balance of the user of different types of soil. We therefore have preferred the interactive shoe described in the previous subsection. While being fitted with the shoe, to move in the game the user has to do some specific gestures that correspond to those that one does face while experiencing a loss of balance. Here we present two different metaphors (accelerometer and force sensor based) that can be exploited for displacements in the game.

20.3.2.1 The Accelerometer Based Metaphor

For this metaphor, the accelerometer attached to the interactive shoe is used in order to detect the gesture performed by the user. Figure 20.3 shows one of the multiple ways for having a shoe-mounted accelerometer. For this configuration, gestures that allow the displacement in the virtual scene are presented at Fig. 20.4. Namely, standing on tiptoe, respectively on heels in dorsiflexion allows moving forward respectively backward. For lateral movements, the orientation of the right

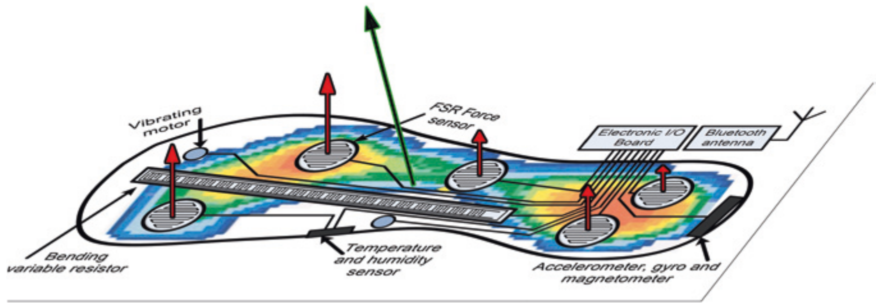

Fig. 20.5 Instrumented sole exploited for navigation in the game. *Arrows in red* are the force measurement at each sensor. The sum of these arrows is represented by the *black arrow*

knee indicates the direction. The main advantage of this metaphor resides in it easiness of usage since it is based on walking gestures. Indeed the four required gestures are found during the phases of walking.

On the technical point of view, being static these gestures are easily detectable by measuring the values sensed by a three-axis accelerometer. With the proposed setup, starting from a neutral position where the foot is laid flat on the ground: standing on heels in dorsiflexion (move forward) increases values of the Z-axis whereas standing on tiptoe (move backward) decreases those values. In the same way, lateral moves can be detected by monitoring values of the X-axis. Indeed, they augment when the knee points the right side and decrease in leftward orientation. One may note that in this case, the Y-axis of the accelerometer is not relevant for the detection of any gesture since the two others provide enough information for this task.

20.3.2.2 A Force Sensor Based Displacement Metaphor

As the named suggested it, this navigation metaphor is based on the repartition of the forces applied to the sole of the shoe. To navigate the user just has to swing (see Fig. 20.6). As shown in Fig. 20.5, two types of sensor measure the forces reparation in sole: the FSR force sensors and the bending sole. Therefore two components let to compute the displacement of the avatar in the scene. The first uses the direction given by the vector forces computed by the (FSR) force sensors. The second component measures the angle of the sole bending to produce a proportional movement in linear direction (forward) (see Fig. 20.7). These components are determined as follow:

- The total force and moment applied on the sole by the user generate a wrench $\mathbf{h}_a \in \Re_{6\times 1}$ which is computed by Eq. (20.1). The position $\boldsymbol{A}$ is the reference frame in the game, $\boldsymbol{B}$ is the reference frame of the shoe, ${}^{A}Q_B \in \Re_{3\times 3}$ is the rotation matrix between reference frame $\boldsymbol{A}$ and its counterpart B. Also, $\boldsymbol{m}$ is the number of sensors inserted in the sole at the position q$\boldsymbol{i}$. $\boldsymbol{B}$ is located at the center of pressure applied on the sole in an upright posture of the user. The vector h_r

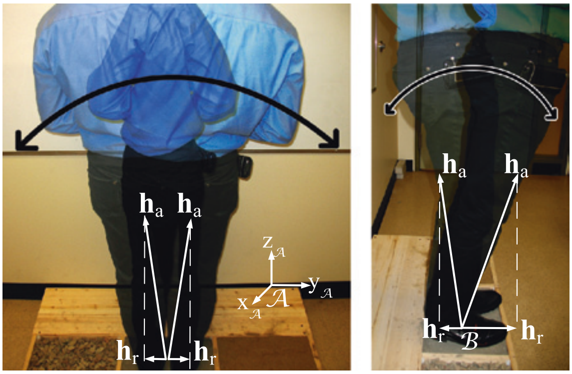

Fig. 20.6 Displacement with the navigation metaphor. Any swing of the user does generate a displacement in the maze

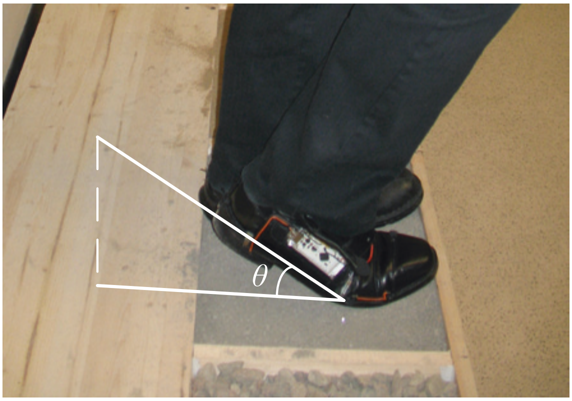

Fig. 20.7 Representation of the direction coming from the bending of the sole

is a projection of the vector h_a on the plane described by the virtual ground; it gives the direction of avatar's movement as seen in Fig. 20.8. The amplitude of the projected vector gives a proportional movement in the maze. In the current version, a Hooke constant k is used to compute a variation of displacement as described by the Eq. (20.2). The current position of the avatar is s_a^n, at the discrete time ***n***.

- The sole bending is evaluated with a bending variable resistor which gives only one angle 0 as shown in Fig. 20.7. This angle is thus used to move forward. Since the bending is proportional to an angle 6, we compute a displacement in the maze ***s***™ with the Eq. (20.4) using a proportional constant ***k6*** which reflects the sole curvature into a linear movement.

$$\mathbf{h}_a = \begin{bmatrix} \sum_{i=0}^{m1} {}^{\mathrm{A}}\mathbf{Q}_{\mathbf{B}}\mathbf{f}_{a_i} \\ \sum_{i=0}^{m1} (\mathbf{q}_i \times ({}^{\mathbf{A}}\mathbf{Q}_{\mathbf{B}} f_{a_i}))n \end{bmatrix} \tag{20.1}$$

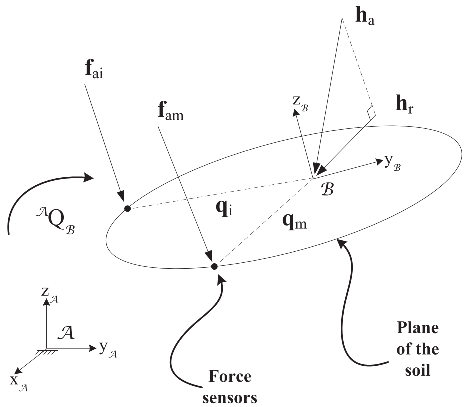

Fig. 20.8 Movement computation in the game used as navigation metaphor

$$\mathbf{s}_a^n = \mathbf{s}_a^{n1} + \mathbf{h}_r/\mathbf{k}, \text{ with} \tag{20.2}$$

$$\mathbf{s}_a = [s_x s_y s_z s_\theta s_\psi s_\phi]^T \tag{20.3}$$

$$s_y^n = s_y^{n1} + k_\theta \theta \tag{20.4}$$

20.3.3 Balance Control: Assessment and Training

The goal of the game is to train people on maintaining balance on different types of soil. Because of that, assessment of the ability of the person to maintain balance plays an important role in the game. A special attention was paid to selection of exercises that can serve this goal.

Literature on assessment of the ability to maintain balance counts two main categories: (1) exercices based or tasks based evaluation and (2) the patient's health. Our game is centered on exercises based evaluation.

Berg Balance Scale (BBS) and Morse Fall Scale (MFS) are two main tools used for fall risk prediction [30]. These tests are very different since the BBS analyzes some tasks (exercises) whereas the MFS approach analyzes the health and the gait of the patient. On the other hand, it was demonstrated that the Heindrich II Fall Risk Model (HFRM) is potentially useful in identifying patients at high risk for falls; some studies suggest that it can be more relevant than both the BBS and the MFS [14]. However, the HFRM approach concerns the analysis of the patient' health and do not cover exercises [12]. The MFS and the Functional Reach test was found to be time consuming and often inconvenient and were not better at prediction than the clinical judgments made by the primary nurses [6]. Finally, the Tinetti Balance Assessment Tool (TBAT) (described in [27]) was also compare with Functional Reach. TBAT seems to be the most suitable performance measure for evaluating balance in community dwelling older people [16]. A comprehensive review of methods to assess the risk of a fall is presented in [13].

As seen through that brief analysis, Berg Balance Scale and the Tinetti assessment tool appear at most appropriate tests for exercises based evaluation. We have therefore integrated exercises proposed in these tests in our game. Proposed exercises are associated with some parts of the maze. During the browsing of the maze, while entering a section associated to an exercise, all motions (used to move the avatar) are disable for the period of the exercise, a video presenting the exercise to realize is shown to the user. In the proposed game, selected exercises are:

- Standing unsupported with feet together;
- Turning in place;
- Placing alternate foot on step;
- Standing on one leg;

With the navigation metaphors (presented in Sect. 20.3.2) and the sensors located in the sole of the interactive shoe (presented in Sect. 20.3.1.1), it is possible to differentiate the four selected exercises compute a score according to the success of the exercises.

20.3.4 Different Levels of Difficulty

The complexity of the game could be described by two components: the maze itself (number of paths, size of the maze and number of dead end) and proposed exercises. At the current version of the game, we do only have rectangular mazes: proposed paths are only vertical or horizontal. Each little rectangle described by the route defines a particular zone and is therefore associated with a particular type of soil (sand, stone, stone dust, wood and concrete). As a result, in the current version of the game, the complexity is mainly determined by the complexity of the exercise to achieve on given type of soil. In general, MFS, TBAT and HFRM use three levels of risk (low, moderate and high). Since we use an additional level of risk in the game (type of soil), four levels of risk (low, moderate, high and very high) are implemented in the game.

At the current stage, the game counts three levels of difficulty. At the easiest level, user is invited to stand on both feet, there is no time constraint for the completion of the task and proposed mazes are the easiest. At the intermediate level, the task has to be completed in a certain amount of time while the mazes are a little more complicated. Although sometime the user has to stand on one foot, most of time he has to stand on both feet. At the hardest level, the time allocated for the completion of the task is reduced and at the meantime the mazes become highly interactive while presenting various obstacles to the user. At this level, when gifted with some bonuses, the user has the possibility to overcome certain constraints of the maze. For example, he may jump over a wall by placing alternate foot on step (the apparatus used for holding the soils as described in Sect. 20.3.1.2). At this step, all the time the user has to stand on one foot. As a result, the use of both feet is seen as a mistake and generates a reduction of the score.

These three levels are designed in order to provide a progressive level of difficulty that will help the user familiarizing themselves to situation that can lead to accidental falls.

20.3.5 Score

To maintain the engagement of the player in the game, we consider all the factors described previously to evaluate a score. The score displayed in real-time is computed according to the execution of the exercise, the difficulty level and the time.

As suggested in the Berg Balance Scale, each exercise is rated on a scale of 0 to 4. The distribution of the forces measured in the sole determines the value accorded for the exercise. In fact, the computed value is inversely proportional to the standard deviation σ of the measured force $|\mathbf{h}_a|$ over the period of the exercise. Hence, when doing an exercise, the user has to stay in a fixed position in order to maximize his score: the more he swings the lower his score for the exercise will be. Each soil type has a difficulty level labelled *D*. The difficulty level associated for soil types are: concrete (or wood): (1), stone dust: (2), stone: (3) and sand: (4). To compute the final score, for each exercise, this difficulty level is multiplied by the score of the exercise. When the time of execution is considered in the game, the final value is inversely proportional to the time *t* with a scale factor *α*, as described by Eq. (20.5):

$$Score = \frac{D}{\sigma(\alpha t)} \tag{20.5}$$

This score aims at evaluating the level at which the user is able to maintain its balance on different types of soil.

20.3.6 Safety Issue

One of the main advantages of using a serious game for balance training resides in the fact that the game can be experimented at home. However, this raises a number of problems related to player's safety. For this, several design choices were made in order to guaranty the safety of the player.

Although the game was designed to train and practice balance control, players should be aware that some of the proposed exercises may represent a risk. For example, previously we mentioned that using deformable soils increase the risk of falling. More particularly, standing on one foot over the sand soil could be challenging for people with balance disorder. Furthermore, the current platform requires a location in a room free from obstructions that may hinder user's movements. Beyond these aspects, in order to prevent potential injuries, at the end of the analysis performed on the data logged from the ECG and those concerning the posture of the player, if a serious trouble is detected, the game is locked and invites the player to contact the costumer service because the game seems not to be appropriate to his profile.

20.4 Initial Experiment

This experiment aims at evaluating firstly the playability of the designed game. At this point, we want to gather information regarding whether users would enjoy or not the concept of using some specific foot gestures in order to move in a virtual environment displayed on a tablet while staying at the same position. Secondly, we known that works have highlighted that the type of soil can affect balance and gait [17, 19], with the proposed game, we want to assess whether we can observe such an effect when making some specific gestures on different types of soil. This point is a major aspect of our work since it will be a good starting point for the conception of a more ecological, automatic and low cost personal rehabilitation system.

20.4.1 Participants and Apparatus

A total of 6 participants (5 males) aged between 20 and 26, were asked to participate in this experiment. Among the subjects, 4 were undergraduate students in science and engineering. The others were graduated student in computer science. Based on our pre-experimental questionnaire, no participant reported having any gait or balance problem. Participants received no compensation.

The maze represented at Fig. 20.9 were the experimented virtual environment and the accelerometer based metaphor was exploited to let the user move. In order to be more enjoyable, the maze was presented in a first person view. Hence while doing the associated gesture, for example by standing on the heel; the user controls the camera of the scene.

In this experiment, participants are asked to travel from the starting point to the finish. For this, users are first presented with the top view of the maze in order to let them see the exact route that they should follow in order to reach the final destination. One may notice that this route was pretty straightforward. Therefore, in this task the difficulty was not at the orientation part but rather in the exploitation of the navigational metaphor. Indeed, in spite of its simplicity, this route necessitates at least three of the four displacement supported by the proposed metaphor namely move forward, rightward and leftward. This design choice has been made since these gestures are the most dangerous for walkers. For this experiment, after a brief

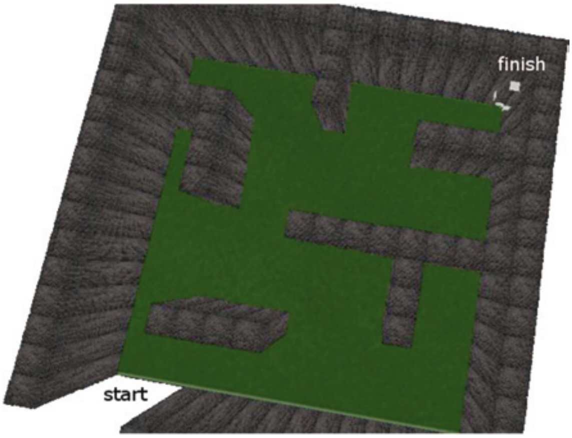

Fig. 20.9 *Top view* of the mazed

Table 20.1 Time spent for each user over the four types of soil in completing the puzzle. Means and standard deviations are indicated at the two last rows

	Concrete	Broken stone	Sand	Stone dust
1	39.382	42.045	47.171	40.952
2	58.719	54.397	48.341	55.584
3	37.662	45.318	51.015	38.605
4	38.766	57.317	41.492	41.941
5	53.567	41.638	40.047	47.561
6	60.376	47.813	40.922	41.723
Mean	48.07	48.08	44.8	44.3
a	10.6	6.49	4.59	6.22

explanation about the goal and the procedure of the experiment users were asked to realize four times the previously described task (travel in the maze), each times while being on a different soil namely broken stone, stone dust, sand and concrete. For each task, in addition to the completion time, we recorded the value sensed by the accelerometer for the Y-axis. What follows presents the results of this experiment.

20.4.2 Results

All the participants realized the task without any difficulty. All the participants reported that the game was really enjoyable; they have particularly appreciated having the opportunity to play a game on a tablet with their foot. Two of them have advocated for more game play that can support various foot-based interactions. Regarding the average of time took for the realization of the experiment, any noticeable difference has been observed. Table 20.1 shows the time spent by each user over the four different types of soil. To analyze the data recorded from the Y-axis of the accelerometer, we used a statistical model. Our model is composed of seven features computed from the acceleration signal: standard deviation, mean,

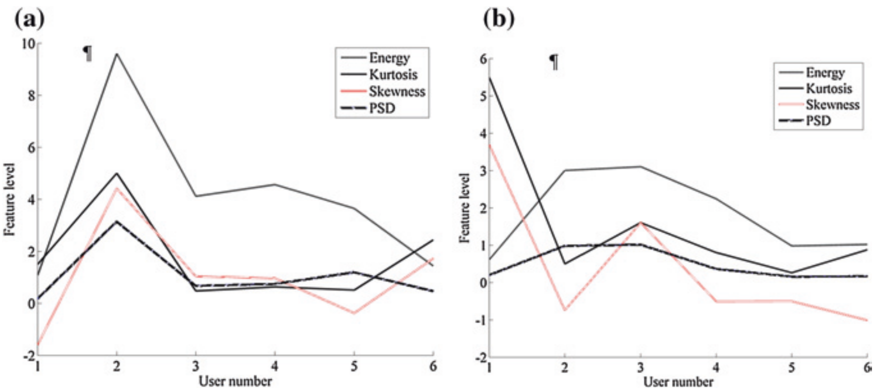

Fig. 20.10 Acceleration features for each user playing on concrete (**a**) and sand (**b**)

kurtosis, skewness, energy, variance and Power Spectral Density (PSD). These features, selected in the proposed algorithm, depends upon the events to differentiate as suggested by [11] and [29] (Table 20.1).

First, the algorithm uses a sliding Hanning windows with a length equivalent to 0.25 s using 2^n samples. Second, the algorithm uses a filter in order to remove lower frequency components coming from intentional movement for moving the avatar in the game and also to remove the flicker noise contained in higher frequency. The remaining signal is thus unintentional movement such as balance recovery motion and white noise. Then, this window is used to compute the features in order to find a difficulty level based on the type of soil. Some features are presented in Fig. 20.10 for the six users playing on the concrete.

The statistical model, described in (20.6), gives a level Lj computed from the sum of n features Fi weighted by a factor W_i in order to detect the actual difficulty level according to the type of soil j:

$$Lj = \sum Wi \times Fi \tag{20.6}$$

Each type of soil gives a Lj which is supposed to be significantly different for all users. The Lj curve is then defined as the difficulty level for each user playing on a soil type. In order to obtain significantly different levels, the factor W_i is optimized for all user and all soil type.

The optimization process is designed in order to increase the difference (and thus the distances) between each Lj curves given by the sum of each acceleration feature. In Fig. 20.11, spectral components are calculated using FFT. It seems that in all situations, users 1 and 6 are not significant to differentiate the level function of the type of soil. This could be explained by an ease to maintain his balance while doing other tasks. To demonstrate the difficulty level concept, these users are removed from the analysis.

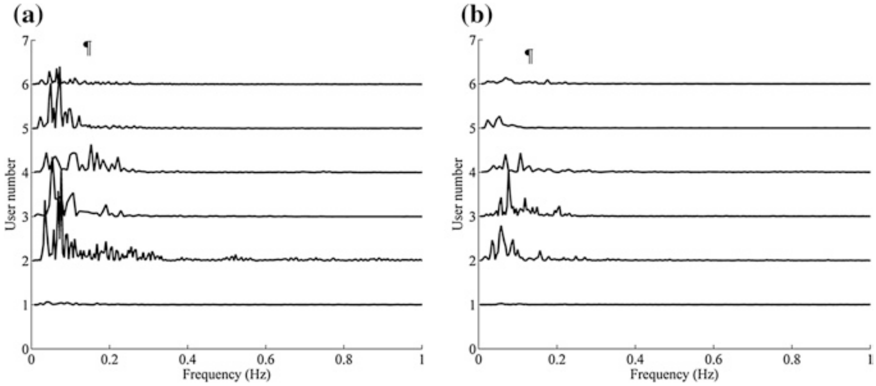

Fig. 20.11 Fast Fourier transform of the acceleration signal for each user playing on concrete (**a**) and sand (**b**)

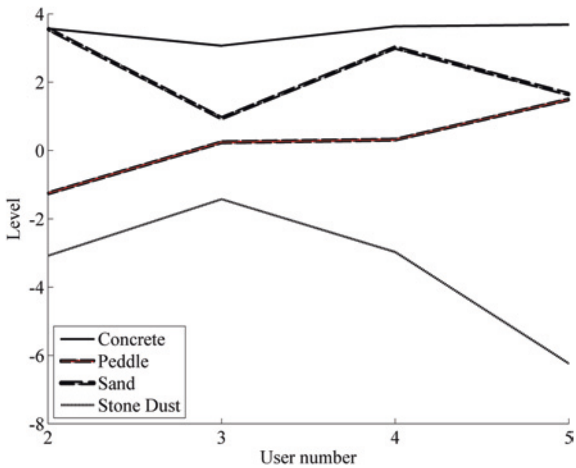

Fig. 20.12 Sum of weighted features after the optimisation process for each user and soil type

After the optimisation of *Wi* in order to separate the curves *Lj*, we obtained the results shown in the Fig. 20.12. The effect of playing on four soil types is represented. From this result, it seems possible to identify a difficulty level for each user and for each type of soil.

It should be noted that the curves are not completely separated, but they do not intersect between each user. Since the equation and the weights are the same for all users and for all soil types, there is still a tendency to differentiate a level of difficulty for the selected soils. The real-time differentiation of the difficulty level could then be executed using three thresholds computed using the half of the minimal distance between each curves *Lj*. As the curves are not separated, those thresholds have to be found for each user. Thereafter, this result may possibly be used in the evaluation of a risk of falling as suggested in [26].

On the other hand, considering that we did use six healthy subjects, in a near future it will be necessary to assess performances of elderly. Nevertheless, one may note that the current evaluation was a mandatory step in order to assess the feasibility and the playability of the system as well as the fun factor of such interactions.

20.5 Conclusion and Future Work

This chapter described a system for training balance control over various types of soil (broken stone, stone dust, sand, concrete and wood). The system is centered on an augmented shoe that the user fits in order to explore a virtual maze. Initial experiment indicates that this system can be useful for assessing impact of a type of soil on a walker.

Based on this we want to develop a home-based setup, for better immersion of the user, the virtual scene could be rendered through a head mounted display (HMD), multiple modalities (haptic and/or audio) [21, 22, 28] and the physical setup is designed in order to let the user walk on the materials. During walking, a motion tracking system can be used in order to track positions of body parts (upper limbs -arms and head-, pelvis and hips) of the user. Using such equipment will not only allows users for training balance over different types of soil; it also will constitute an environment that can help at analyzing how a particular type of soil affects the gait of a given user and how assistance should be provided in such an environment.

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Part V
Therapeutic Games Aimed at Various Diseases

Chapter 21
Computer Games Physiotherapy for Children with Cystic Fibrosis

Andreas Oikonomou, Dan Hartescu, David Day and Minhua Ma

Abstract Sufferers of cystic fibrosis and other chronic lung diseases benefit from daily physiotherapy such as Positive Expiratory Pressure (PEP). For children, however, such repetitive daily exercises become a burden and may lead to confrontation with the family. Using a system comprised of a PEP mask, a computer-connected pressure monitor and a suite of games of varying types, a series of tests will determine with both objective statistics and subjective feedback how effective the system is at encouraging children and young adults to participate in daily therapy. With longer and more advanced games, coupled with unobtrusive data gathering functionality, we determine what effect long-term use of such a game system has on young sufferers. The study has shown that games based PEP physiotherapy is a desirable, viable alternative that can perform at least similarly to the existing approaches in terms of the amount of time children spend engaging in breathing exercises and with potentially many additional benefits including the capture of detailed data about the amount and quality of physiotherapy which is currently impossible with conventional, non-computerized methods.

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21.1 Introduction

Cystic fibrosis is one of the most common life-threatening diseases in the UK, with over 9,000 sufferers. The World Health Organisation estimates that 1 in 2,000–3,000 newborns are diagnosed with cystic fibrosis in the EU and 1 in 4,000 in the United States [1, 2]. Sadly, only half of the current sufferers are expected to live past 41 years of age, but that number is slowly increasing with improving treatments [3].

The condition is caused by a faulty gene which controls the transfer of salts and water through the cell membrane in the human body. When this gene is expressed, it affects internal organs, especially the lungs and digestive system, clogging them up with mucus and making breathing and digestion difficult [1].

Mucus build-up in the lungs leads to the clogging of airways and inflammation, which increase the change of infection of the respiratory tract. Initially, the sufferer exhibits increased phlegm production, coughing and reduced ability to exercise. Later, when the bacteria inhabiting the mucus grow out of control, pneumonia and other infections become common. Further on, damage to the lungs and airways may occur, leading to even more difficult breathing. Symptoms become worse with time, which is why cardiorespiratory complications are the most frequent cause of death (around 80 %) for cystic fibrosis sufferers [4].

Cystic Fibrosis cannot be cured, but its symptoms can be actively managed by a combination of physiotherapy [5], exercises, medication, and diet. Physiotherapy plays an important role in managing the disease as it clears the mucus and frees the air ways.

The most common physiotherapy technique is Positive Expiratory Pressure (PEP), which uses a mask to open the airways and, by repetitive breathing exercises, helps loosen the mucus in the lungs. Depending of severity and amount of secretion in the lungs, the exercise should be performed between 1 and 4 times a day, with duration ranging between 10 and 15 min for maintenance sessions, up to 45–60 min sessions for loosening a heavy build-up of secretions [6].

While adults regularly engage in PEP physiotherapy exercises, children sufferers often see this task as boring and repetitive, and parents often have a hard time convincing them to perform these activities regularly. While adults see the medically beneficial value of such daily exercises, children are put off by the lack of challenge or fun in such a mundane task.

The idea therefore is to add a gaming element to the exercises and through that present enjoyable challenges and reward correct behaviours in order to improve engagement with the physiotherapy exercises. Games are known to stimulate and hold a player's attention for long periods of time, especially in the case of children and young adults, and are used in this project to leverage repetitive action into creating engaging experiences that put players in a state of flow making them lose track of time spent.

The proposed system couples PEP therapy and game mechanics through a set of games and associated hardware controller to gauge the engagement of children with cystic fibrosis.

21.2 Previous Work

21.2.1 Airway Clearance Therapies

Throughout the life of a cystic fibrosis sufferer, managing the build-up of secretions and clearing the airways takes the longest time out of all other aspects of treatment. There are multiple ways to clean the airways, according to study in the field, that differ in applicability, practicality, ease of use, cost and time commitment. In a comparative study presenting seven different types of Airways Clearance Therapies (ACTs), researchers [7] analysed the efficiency of each one and objectively assigned recommendation grades based on multiple factors. The findings are addressed to both cystic fibrosis sufferers and physicians as a guideline for determining what ACT is best for each patient.

Overall, the study showed that existing literature comparing different ACTs showed no objective benefit of one airway clearance technique over the others, but it did present evidence that using such therapies is more beneficial to the patient rather than using none of them in short-term tests, even if little long-term data was available [8].

It was also found that, while on average no technique is better than the others, at an individual level some may be more appropriate, and determining these should be the result of testing and discussion between patient and doctor and based on factors such as age, preference and adverse effects. The research also suggests therapy should start as early as possible after detection of the condition, even at just a few months of life, with appropriate adjustments.

The ACT relevant to our study is the Positive Expiratory Pressure (PEP): breathing assisted by a device against a pressure of 10–25 cm H_2O generated by a resistor (e.g. valve) to assist in raising the functional residue and re-inflate collapsed lungs. Alternatively, a high-pressure PEP can be used, with the resistor set at 40–100 cm H_2O.

21.2.2 Breathing Therapies for Children with Cystic Fibrosis

Therapy usually begins right after diagnosis, if the child is healthy and old enough—above 4 weeks and 3 kg. The type of therapy recommended, and whom it is performed by, depends on the age group of the child.

As recommended therapies for older children become more complex, with a higher focus on responsibility and self-organisation, one constant system remains present throughout the list: the adoption of scenarios of play. From infants who interact and laugh with their parents, to toddlers and small children who are encouraged to take part in games with family and friends, to the suggestion of sports for older children, the advice that physical therapy be coupled with fun play-like activities remains a constant.

This is understandable as, while adults have a better understanding of cause and effect and can see benefit in routine, albeit uninteresting therapy sessions, children lose their patience and their focus and must be entertained by an activity in order to return to it voluntarily. Among parents with young children suffering from cystic fibrosis, one of the most frequent comments is that the hardest part of airways clearance therapy is getting the child to commit to it.

In a 2007 study [9], 34 cystic fibrosis patients of ages between 1.6 and 40.6 years were given a self-administered questionnaire regarding their compliance to the treatment prescribed. The results were later cross-referenced with subjective reports from the medical staff that had cared for them. The report suggested that a large portion of patients were compliant with digestive (88.2 %) and respiratory (61.8 %) medication, while fewer complied with nutritional supplements (59 %) and even less with physiotherapy (41.2 %).

In Prasad and Cerny [10], factors that affect adherence to exercise programs and therapy were tested. For a starting point, factors encouraging healthy children to adhere to an exercise regime were discussed: social support, feelings of competency and self-esteem, enjoyment of the activity and a choice of various activities all push children to commit to a program. The study determined that these factors still play an important role for children suffering from cystic fibrosis, but the added conditions of fatigue and time constraints for the therapy add challenge to compliance with the given program.

21.2.3 Adding Play Elements to Therapy

Some therapies and devices aimed at children have adopted a toy-like aspect and are used in a game-like fashion. Toddlers are too young to engage in therapy by themselves, so the PEP device is used with an attached baby mask and is handled by the parent. As children grow older, therapies become more goal-oriented and game-like to engage children and help them adhere to physiotherapy easier. One example is the standard PEP valve coupled with a manometer as shown in Fig. 21.1. The goal of the exercise (or game) is to keep a constant pressure in the lungs, indicated by keeping the pressure indicator on the manometer constant, between two points, while breathing for as long as possible.

Another PEP device aimed at children, the Bubble PEP, is based on a similar concept: with a tube inserted in a bottle half-full with bubble liquid. The goal of the game is to blow until the bubbles flow out. This is accomplished with long breaths which help to release mucus while the act of blowing bubbles and the colourful display engaging children. An important aspect of this device is that it is very easy to improvise, with components easily available in most households.

The Acapella device (Fig. 21.2), similar to the Flutter, is used in oscillating PEP to create vibrations in the chest by blocking the path of air in an oscillating manner. The vibrations help release secretions from the lung walls. Though the device does not produce musical sounds, its frequency can be toned and the user

Fig. 21.1 PEP valve and manometer [24]

Fig. 21.2 Acapella PEP device [16]

is encouraged to perform different breath patterns such as long, sustained ones or short, high power bursts, with different sounds for each one, functioning similarly to toys that make rattling sounds.

In the absence of medical therapy devices, normal toys can be used for effective and fun breathing exercises. Simple toys that can be used for this purpose include whistles and toy trumpets, harmonica, paper windmill, polystyrene plane with a straw, and bubble blowers.

Even without toys to assist in therapy, or when the child is too small to use some of them, parents can play small games with their children to encourage them to perform breathing exercises. A patient information leaflet published by Cambridge University Hospitals [11] details possible breathing games that can be played without medical equipment:

- Blowing bubbles: mimicking blowing a bubble by forming an 'O' with the mouth and exhaling gently, as with the toy
- Cotton wool balls: placing a ball of cotton wool, the parent encourages the child to blow the balls out of their hand. Additionally, this can be a competitive game, where parent and child compete for who can blow their wool ball furthest
- Cotton wool football: with straws and a 'goal' made out of a box, the parent places a wool ball on the table and asks the child to move it, by breathing through the straw, and score a goal.

- Lifting a tissue: holding a tissue from the top 2 corners, the parent asks the child to blow slowly as to lift the tissue almost horizontally, and keep it there for as long as possible
- Blow painting: with a few drops of paint on a piece of paper, the parent asks the child to blow, through a straw, and move the droplets as to make a painting.

The document also suggests parents keep a weekly activity list, marking what kind of exercises have been performed each day. This serves a dual role, both as a review tool, to identify what games have been played most and which ones yield the best results, and as motivation for the child, as seeing improvement over a period of time in one game can give a sense of achievement that is fundamental in improving adherence to physiotherapy.

Sports and physical exercise should be the most important once the child is old enough, but games such as these can be fun and engaging, and they are quick, cheap and safe to play.

21.2.4 Switching to Digital Games

Real-life games can be fun to play and are more physically engaging, but they suffer limitations: they are material and position dependent. You cannot play blow painting without some paint, or you cannot blow bubbles without bubble solution. Even with imagination involved, there is so much that can be done before physical constraints limit the experience.

Another issue is player tailoring: toys may come in different sizes, PEP valves with different resistances, but in the end the player is limited by the selection of products the manufacturer markets. A new device idea takes time and is very costly to research, design and manufacture, and without a sufficient consumer base, producers would not take the risk.

On the other hand, digital games have few limitations in terms of creativity: game developers can create expansive worlds with few resources and a variety of gameplay approaches to suit a wide range of players.

The downside is that, while physical games don't have a limit on what actions the players can perform, as long as they are within the rules, digital games have a strict set of controls and limited input devices. The limits on interaction with software and games are fading with rapidly advancing technology: the Kinect allows for full-body control, while existing head and face-tracking are being integrated with games, leading to a very near future where a virtual avatar can be precisely controlled in terms of gesture and mimicry. The challenge then falls on the game designers to accommodate for the wide range of interactions players have available.

For this specific case, however, there is limited control in the breathing exercise games themselves. The players have a task to perform which involves different types of exhaling, either in short powerful bursts or long, sustained breaths. Mathematically, this means either reaching a high pressure for a short time—or repetitive peaks of pressure output—or keep pressure at a certain level for an amount of time, all of which can be programmed with an analysis of pressure measurements from a device per time unit.

21.2.5 Existing Games for Cystic Fibrosis

Very few existing games have been developed for cystic fibrosis physiotherapy. In 2010, Bingham et al. [12] sought to test spirometer-controlled video games to determine if these would promote breathing techniques in children suffering from cystic fibrosis. The game itself consisted of a target moving in one dimension and players had to track it using their breath. The trail was performed on a group of 10 inpatients, hospitalized for cystic fibrosis exacerbations. The candidates spent at least 15 min with the device and game and reacted positively to the experience. Over 5 sessions, statistics showed that the patients' eye-breath coordination had increased.

This initial research used a small pool of candidates in a hospital environment; therefore the statistical results are limited. The game component itself was limited in terms of mechanics and depth. However, feedback from the game showed that it promoted breath awareness and could be used to foster social ties among children with cystic fibrosis.

This research was later extended through the development of two complete games (*Ludicross* and *Creep Frontier*) that used a spirometer as a main control method [13]. The premise was that children refuse to adhere to airways clearance techniques, preferring instead to play games that challenge their dexterity and coordination; by using games as a delivery platform for such exercises, the research examined whether patient engagement was increased and whether the games had any effect on pulmonary function tests.

In *Ludicross*, players drove a race car down tracks by breathing into the spirometer (Fig. 21.3). The longer the breath, the more the vehicle accelerates. Additional elements such as obstacles, speed-up and slow-down areas are present on the track. Besides racing, the players can also refuel their vehicle and wash it.

The game *Creep Frontier* revolves around exploration and combat. The game world is being infested with sludge that corrupts the flora and fauna and the players, called *Creep Riders*, travel around, exploring the wilderness and fighting sludge to save the environment (Fig. 21.4). Fighting is performed by blowing bubbles—through actually blowing into the spirometer and eliminating sludge covering animals or plants.

Both games are lively, colourful and designed to be fun to play and associate the idea of breathing exercises with a playful, light-hearted atmosphere. 13 players, with ages between 8 and 18, participated in two phases of the study: a control phase and a game phase. The control phase was used initially to determine a baseline for pulmonary function tests (PFTs) and was used as a comparison to the second phase. Patients had access to the same spirometer device in both phases, but could only play the game in the second one.

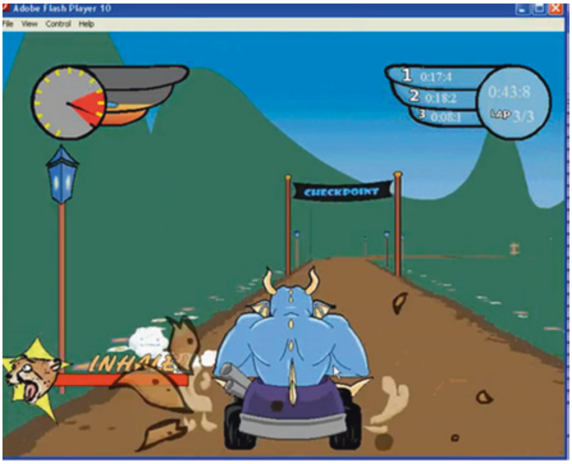

Fig. 21.3 Ludicross racing game [25]

Fig. 21.4 Creep Frontier [25]

The results showed that, before the study, few subjects were carrying out regular breathing exercises. During the study, however, they performed huffing exercises more frequently than before, but in similar amounts in both the control and game phases. A difference was noted, however, in the forced vital capacity—namely, the ability to take bigger breaths—during the game phase, as opposed to the control one. Overall, there was a tendency in spending more minutes performing exercises in the game phase, and that statistical analysis showed an increase in vital capacity after the game phase, though this may be attributed to an increase in experience rather than actual lung capacity [14].

Though the pool of subjects is relatively small and the statistical tendencies need further research to confirm, the experiment shows that children have the tendency to get involved and spend longer times in games. The fact that the games are short and simple is not an issue, since the therapy sessions are only supposed to last around

15 min daily. The cartoon style graphics and lively colours and characters, however, are bound to elicit a more favourable response in younger audiences, especially preteens, while older teens are likely to dismiss some content as too childish. A more in-depth study with younger children (even kindergarten age) would give better results relative to the target market of such games.

One disadvantage of the previously tested games is that they use a digital spirometer which, while being very accurate and useful, is an expensive piece of equipment, often requiring detailed technical and medical knowledge to use successfully. These devices are available in hospitals, where trained staff can assist patients, but they are not a good platform for end-user systems due to the high cost. A cheaper and more portable device, even if less accurate, would be better suited for use at the patient's premises.

21.2.6 Building on Our Previous Work

The current project is based on our previous research that prototyped the games and device and that tested, to positive results, the engagement of children undergoing PEP therapy when using such a device [15]. The previous system was composed of a computer-connected pressure measurement device, a PEP mask, given freely to cystic fibrosis patients, software libraries that controlled the pressure sensor and a trio of short, small games that varied in mechanics and theme. The games used different mechanics that matched PEP therapy techniques:

- Peak Flow Rate (PFR): an exercise consisting of short, high pressure and volume exhales
- Forced Vital Capacity (FVC): an exercise in which the patient is encouraged to prolong the exhale as much as possible

The games were tested on one child and appeared successful with parents often claiming that they had trouble getting their child to stop playing. With the feedback received, notes were taken of what mechanics were readily accepted and which ones were perceived as annoying. Even with the limited scope of the games, the child quickly accepted and preferred the games to the traditional physiotherapy approach. However, in the end the parents opted for an alternating routine between using the games and their original physiotherapy method. While the games were very successful in drawing more attention from the player than regular exercises, the limited number of mechanics of each game ultimately became boring and the child lost interest after an average of 8 minutes.

While the previous project received positive subjective feedback to warrant further development, the objective data such as time spent playing, were insufficient. For these reasons, we improved the previous games by adding varied game mechanics and making the games longer. We have also provided a mechanism for accurately measuring a variety of statistics that are detailed later in the results section. Those, combined with additional subjective feedback from a bigger test group have provided more essential information for determining the usability of the system. These will help take the project further forward towards ultimately testing its potential therapeutic benefits in a clinical trial.

21.3 Materials and Methods

The main objective of this research is to determine whether digital games can be successfully used as an incentive for young children suffering from Cystic Fibrosis to adhere to breathing physiotherapy. Additionally, gathering sufficient data with regards to time spent playing, breathing statistics and player feedback leads to a better understanding of how much medical, physical and mental benefit such a system can offer and how future systems can be improved.

Because of the scope of this project, multiple levels of research must be performed and data must be collected and analysed from a variety of sources. Two trial phases were conducted: a baseline trial and the gaming physiotherapy. To yield accurate results, patient exercises were as similar as possible between the trials. The experimental devices and software used by the patients were the same. Frequency and duration of therapies were also kept consistent throughout both trials.

The main focus of development was the games and the hardware device. Those should fit easily into the daily routines of CF sufferers. The device should fit the existing medical devices that the players use while the games should be compatible with the users' existing computer platforms.

Objective data from the trials were recorded and updated after every therapy session. To ensure an accurate statistical analysis, data collected from users were checked for consistency and redundancy. Subjective data was equally important because it gauged the participants experience with the system and is the best source of information for problems, improvements and possible future work.

21.3.1 Gaming Hardware

The input device was built in-house with components available at electronics shops. It is composed of three main parts: the breathing apparatus (mouthpiece) and connecting tube, the pressure sensor, an Analogue-Digital (AD) converter and the computer connection.

There are devices which combines multiple components in one package. For example a digital spirometer such as the Piko-6 Digital Lung Function device [16] combines a mouthpiece, pressure and air volume sensor, digital conversion and memory functions as well as infra-red communication hardware for communication with other devices. All-in-one devices such as this can be portable and versatile but their functions are very advanced and while useful for medical personnel they may be too difficult to operate by patients. The price range (around $100) is also a factor that may deter patients from acquiring them.

Fig. 21.5 The PEP device, with splitter attachment and restrictor valve

21.3.1.1 Breathing Apparatus

The component with which the patient has the most contact is the mouthpiece, therefore it must be a device with which they are familiar and comfortable with. While any simple tubing would suffice just for a pressure reading, allowing natural breaths, without removing the device, is optimal for the patient experience. It should also be adaptable, with different restrictions on air flow for different patients.

One of the devices most used in physiotherapy is the Astra Tech PEP device (Fig. 21.5). It is a small plastic device with one opening for the mouthpiece and two that restrict air to inward and outward flow. The transparent part is connected to the mask, which is different for adults and children, and allows inhaling and exhaling; the blue end is for air intake; and the white end is where air exits through. The white end is attached to a splitter with a small tubular exit and a larger opening where the resistor valve is placed. These valves come with different opening sizes to vary air resistance according to the patient profile.

Cystic Fibrosis patients receive this device for free (in the UK) from NHS—implying that most sufferers already own such a device—and that they are easy to clean, lightweight and highly adaptable makes them a perfect breathing device to be used in a project like this.

21.3.1.2 Pressure Sensor and USB Interface

To digitally read air pressure in the breathing device, an electronic device is needed. Such a device must be able to communicate with other equipment which processes the readings.

Digital manometers are mainly used for high pressure readings, making them unusable in a medical application [17]. Medical manometers are generally used in blood pressure devices (sphygmomanometer) and are analogue. The digital ones are either part of a larger device or are very costly by themselves. To minimize costs and reduce size, we decided to construct our own digital pressure sensor using integrated circuits. This gave us the freedom to choose between from wide range of products those that would have adequate specifications with the smallest investment.

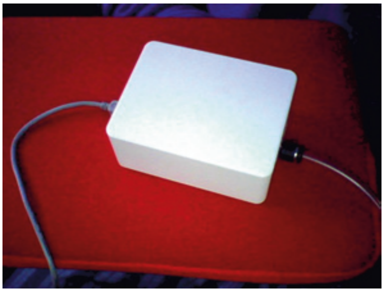

Fig. 21.6 New iteration of the device housing

The first component to choose was the pressure sensor chip. There are many such integrated devices, an analysis of which is beyond the scope of this chapter. The device we adopted was one of the MPVZ4006G line of pressure/force sensors developed by Freescale Semiconductor [18]. There are several reasons we made this choice:

- It is small. Only 10.7 by 18.4 mm with pins included
- It has very low power consumption (5 V at max 10 mA, 50 mW total)
- It has good accuracy (±2.46 % at normal room temperature)
- It has a sufficient pressure reading scale (up to 612 mm H_2O)
- It can be attached to a tube
- It is relatively cheap (around £9 per unit)

While the pressure range on this device is low (compared to more expensive alternatives), we must consider that

- This project is intended for use by toddlers and small children (pre-teens)
- The reported maximum pressure of exhalation was around 960 mm H_2O for boys and 800 mm H_2O for girls (age 11–16) [19]
- The pressures above are maximum static pressures, while free-flowing air pressure is significantly lower [20]
- The breathing exercises don't require maximum effort, just above a specific level of pressure

With a sensor chip selected, the next step was to determine a digital device that would power it, read the input and transfer it to a computer. Since the sensor is a small, 5 V device with pins as connectors, it needed to be mounted to an Analogue-Digital (AD) convertor circuit that would then itself be connected to a USB interface for communicating with a computer.

The development board we chose is the Velleman VM167 interface board for its simplicity, small size, low cost and low power usage. The VM167 is a USB-powered Input/Output board with an integrated Analogue/Digital converter. The device allows easy control through calls to the provided DLL, permitting any application that supports such calls to connect to it.

Connected to the PEP device is the digital pressure sensing device encased in white plastic electronics housing, 60 × 115 × 25 mm in size (Fig. 21.6). Available from most

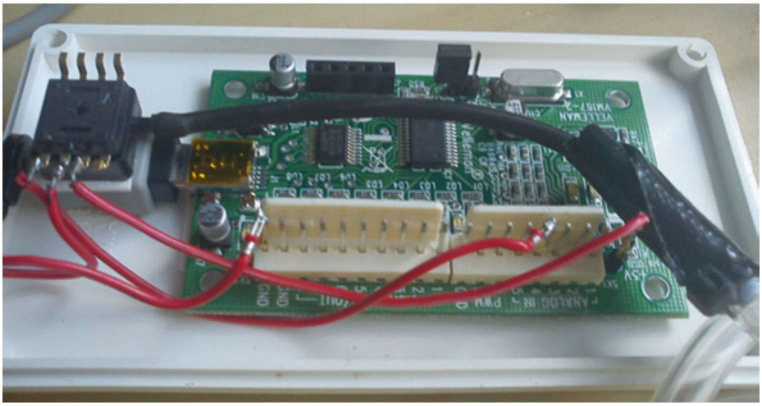

Fig. 21.7 Device electronics

electronics and DIY shops, the housing is locked by four screws on the underside, with two connection ports on the edges for the connecting wire and air tube. It permits the removal of both air tube and mini-USB cable, for transport and storage, without opening the box.

Inside the housing (Fig. 21.7) sits the MPVZ4006G pressure sensor, connected through three wires to the AD converter/USB interface, the Velleman VM167. The pressure sensor is connected to a transparent tube that fits, at the other end, on the PEP device's small opening on the output splitter. Air pressure is kept constant throughout the white end, splitter and air tube when the user exhales. Because of the restrictor valve, air flow in exhalation is impeded and pressure increases in the chamber, though it is not static pressure as the valve is open-ended. The device connects to the computer through the USB port to the mini-USB interface and, which serves as both the data and power line.

The games are designed to use the device for most mechanics, but they also require traditional input devices—keyboard and mouse, to operate the menu structures and use advanced features.

21.3.2 Collecting Game Data

To determine whether the games we developed help children suffering from cystic fibrosis engage more with physiotherapy, we need obtain direct feedback from players on whether they have enjoyed the games and how the games could be improved. Catering to player preference increases the chance they will play the game again, increasing the time they spend performing breathing exercises. Creating engaging and entertaining games puts players in a state of flow [21], where they lose track of time and immerse themselves in the game, which would make them consider the time spent not as a chore but as relaxation. Suggested daily therapy has to be performed at least for certain amount of time, but it can go on for as long as the player wants, possibly improving lung functions with longer time [14].

From previous experience, we know that patients' self-report of duration and frequency of therapy sessions with the games were often inaccurate, and this is expected especially if the games are engaging enough to lead to the state of flow. For this reason, game data needs to be recorded. This not only offered the opportunity for more detailed statistic analysis, such as number of breaths or average breath length, but also eliminated the responsibility of players or their parents to keep track of the playing activities.

The first thing to consider when building an automatic statistics reporting tool is what kind of data to include. Time values, such as time when session started and duration of session were naturally included. But since the games feature menus and the ability to pause, we decided to also record how much time the player actually spent in-game, as opposed to either paused or in the menu.

Furthermore, we wanted to analyse how breathing functions change with subsequent sessions. We recorded how many breaths a player takes in each session, but also how long the average and maximum breath were. Since the device reports pressure as the indicator of breathing, the average and maximum exhalation pressure for each session were recorded as well.

The objective data was collected in the form of game statistics, including

- IP address for identifying different players
- Player age for research purposes (age-based preference of games)
- Game, level, score and number of deaths (for game-based statistics)
- Start and end time of the session (server-side values)
- Time spent with a game (total), in-game and in-menu (for redundancy)
- Maximum pressure, average pressure
- Number of breaths, average breath time, maximum breath time

Each game also has its specific statistics. All game data is sent to a central server through an automated process. We used an online hosting service with database access. The standard service we chose offers 10 MySQL databases of 1 GB each, which is sufficient for the storage of the game data collected. To connect to the database, we developed a server-side PHP script which updated the database with variables received through POST. Since the connection string and POST variables are embedded in the game code and the script resides on the server, configured to only work with the correct parameter order, the system is secure for average users.

The software was configured to send data to the server at two points: when the game starts and ends. The game start update was used mostly for server-side timestamping and redundancy check. Most variables and parameters were updated at game end, right before the application closed properly. Therefore, if initial data was present in the field but no parameters had been sent, it was probable that the application ended in an unusual way, either bug or forced termination.

The update procedure is unnoticed by the player, with the connection being established in a background thread to let the game run in the meantime.

21.3.3 Collecting Player Feedback

Collecting subjective feedback from participants is a key element of this project as it shows whether the games were positively or negatively received, regardless of individual performance.

To collect such data, there are several options to choose from: interviews, focus groups, and questionnaires. Due to the scope of the project and the fact that the experiment takes place at the patients' home, the best way to obtain feedback was through distributing online questionnaires. Another possible method to collect information would be through unstructured emails from participants. While these may contain good quality subjective feedback related to the interests of participants, their unstructured nature makes it difficult to perform statistical analysis. In order to obtain the best results we adopted an unstructured, email-based form of feedback during the development and in-house testing phase and a structured questionnaire in the larger, usability testing phase.

21.3.3.1 Usability Study

A total of 14 participants, children between the ages of 2–12 took part in the usability trials. The trial lasted for 14 days and two types of data were collected: the baseline, non-computer PEP exercise data via questionnaire and the game data via the software.

Usability questionnaire for the game therapy group

The purpose of this questionnaire is to gather information about participant's gaming history, impressions of the game experience and suggestions regarding improvement and future research.

The first part of the questionnaire asks for information regarding previous gaming experience: how often the child plays video games, what kind of genres the child prefers and what kind of devices the child usually plays on. The section also asks whether participants have ever interacted with digital games meant for therapy and if so, what their opinions are on their effectiveness. The information gathered in this section is useful in discerning how experience with previous games may have affected players' expectations and impressions of our games.

In the second part, a series of statements are listed to which the participant responds by selecting the box that best describes his own impressions. The answers are organised on a scale of agreement to the statement, from "completely disagree" to "completely agree". The statements describe a few game aspects for which we are interested in gathering player feedback.

In the final part of the questionnaire, the player was asked to give subjective and detailed answers: from a list of features, they are asked to identify which ones they enjoyed the most and the least and to give brief explanations for the choices made. This section is important to identifying what aspects need to be improved in future iterations or similar projects.

Questionnaire for the control group

During the usability trial the 14 candidates that participated in the study had to provide 2 weeks' worth of baseline data without using the games. This was necessary for gathering comparative data between the default therapy sessions—just using the PEP device and performing breathing exercises—and the game therapy sessions.

To acquire baseline data a questionnaire was created to be completed by the participants with data regarding their normal PEP session statistics. The purpose of collecting this data was to compare child engagement and attention span between standard therapy sessions and the later, therapy-oriented gaming sessions.

The first part of the questionnaire included questions related to parameters of the child's PEP therapy sessions, questions which needed just one answer at the start of the period. It asked for information such as:

- Average duration of PEP therapy per session
- How many times PEP therapy sessions occur daily
- Number of repetitions per set each session
- Number of sets per session
- Times of day when PEP therapy is performed

The second part of the questionnaire included information that was to be filled in on a daily basis during the trial. It contained 3 tables that had to be filled on a per session, per day basis, gauging parameters such as ease of persuading the child to perform PEP therapy, ease of maintaining the child's interest throughout the predetermined number of sessions (once or twice over a 2 week period) and whether or not the child had to receive incentives or be threatened with discipline to comply with the therapy.

These information fields, generally filled in by parents, were later used to estimate a baseline child engagement in PEP therapy.

21.4 Game Development

We have developed a suite of games controlled by breath to encourage children to participate in airway clearance therapy. The software, however, extends beyond the scope of just games: connection to the device had to be established and data from the pressure sensor read, pressure data had to be translated to in-game actions, the same data had to be summarised and recorded in session logs. Software for all these functionalities had to be developed to allow seamless communication between the games and supporting services. The project success depended on all components, communication with the device, good measurements, reading and storing data. Once these aspects were implemented, we then focused on creating and improving the games.

21.4.1 The Target Audience

Games can be of a variety of types, genres, difficulty levels, aesthetic styles, but the most successful ones are those which cater best to their target audience and balance all elements of game design in a way that is appealing, challenging, and entertaining.

The first step was to determine what audience the games were aimed at. One of the main aims of the project was to bring physiotherapy in the form of games to young children, specifically the pre-school and early school years. This implied that the games had to be tailored to this age group: simple to understand game metaphors, fun cartoony graphics, non-violent themes, and quick to pick up and play.

The young age of the children implied that text should be used sparingly, as some participants would be too young to even read, instead opting for intuitive design and tolerance for mistakes and occasional assistance with flashing symbols, bright colours and other visual cues. With such a young audience in mind, story and consistency were not as important: simplistic stories with archetypal characters, logical fallacies in favour of simplified reasons or non-realistic mechanics that don't need an explanation as long as they are interesting and fun are all common in games for young children.

Our candidates for testing were both males and females, adding the challenge to design a range of gameplay to appeal to both genders. This implied we had to avoid overtly masculine or feminine aesthetics and aim towards a more gender-neutral approach to gameplay.

21.4.2 Artistic Style

When creating games for young children, the aesthetic must draw them in by catering to their imagination and help them understand the elements without lengthy descriptions. A good approach is inspiration from popular media that cater to that age group. TV programming and cartoons are generally brightly coloured, often in an exaggerated fashion, with caricatures that emphasize traits and are used for comedic purposes: characters often have disproportionately large heads, eyes and hands, their facial expressions are exaggerated, their reactions energetic and physical.

For inspiration, we used popular BBC programmes for young children, such as shows from the CBeeBies program: Cloud Babies, Waybuloo, and Octonauts [22].

The style we chose for the graphics was a hand-drawn cartoony theme with uneven lines to suggest a comedic approach. Some assets were rendered in 3D and then enhanced with 2D details drawn over. This style worked well as most of the assets were static or with few frames for animation, and the details added to the overall feel.

3D control in games offers more freedom and improves immersion as the game world seems closer to reality. On the other hand, 2D perspective and control implies a simpler, more approachable mechanic. Distance and direction are easier to estimate in a parallel-projection 2D view than in 3D. For this reason, some games are better suited for a 2D perspective, such as platformers, side-scrollers and top-down games. 2D is also faster and easier to develop for, and does not use as many resources as 3D perspective.

Considering the time limit imposed on developing the games, as well as the intended audience, we decided to pursue a 2D perspective and mechanics for our games. As most games for young children tend towards a 2D perspective, including our sources of artistic inspiration, the style of our graphics would fit better in 2D games.

Because of its ease of developing simple 2D games, full range of features and compatibility that allow interaction with the breathing device through DLL calls, we chose the GameMaker [23] to implement the games. GameMaker is optimized for the creation of 2D games, with built-in collision detection, image editor and rendering functions and is easy to use, and it also allows room for improvement with DLL compatibility and extensions. Furthermore, with additional modules, it allows the creation of games for iOS, Android and HTML5, making games compatible across many operating systems and platforms.

21.4.3 Game Metaphors

In accordance with the purpose of the project, the main mechanic to be used in all games was breathing through the device. From a design perspective, this raised the challenge of how to map breathing to in-game actions in a metaphor that makes the sense for the player.

To solve this, we searched for ways in which blowing in real-life can be used to interact with objects. The act of blowing onto a bunch of small objects is related to scattering: leaves, dust, confetti or dandelion seeds. Blowing is also used to inflate objects, such as balloons or tires. Blowing is also used to push light things such as napkins, cotton balls or toy ships. Blowing can also be related to movement in the air: flying, gliding, going up in a hot-air balloon and so on. Finally, blowing can be easily connected to breathing in games, such as blowing fire or replenishing energy or fuel.

We intended to associate some blowing actions in the games. In the *Flower Garden*, we wanted the player to interact with on-screen objects, e.g. spreading seeds, blowing in a windmill, pushing water or shooing away birds. The *Pirate Quest* emphasizes exploration. We connect the act of blowing with movement in

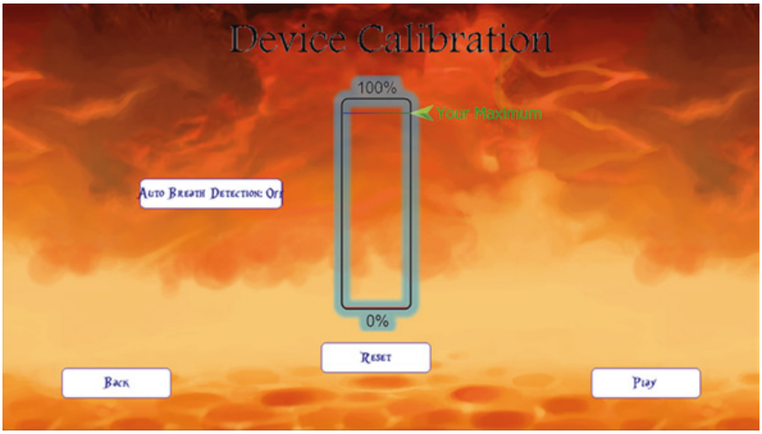

Fig. 21.8 The calibration menu is similar for all games

a logical way. For this we chose a sea adventure, where 'blowing' into the sails of a ship pushes it across the water. In the *Dragon Caves*, exploration and combat were used. We connected blowing to movement and firing. Being a side-scrolling, platform game, blowing does not apply to horizontal movement very well. Jumping and vertical movement can be connected to blowing by using wings to go up or glide. Breathing fire is the most logical connection to combat, with stronger breaths causing more damage or range in game.

21.4.4 Pressure Mechanics

Breath is measured in the game as an increase in pressure above the idle point. Using the absolute pressure amount, however, may not be suitable for all users, as some may feel more comfortable with lighter breaths than others. Therefore, we decided to use the pressure ratio: instead of reading the pressure value, each user defines his own maximum pressure and the system reports the ratio of the current breath compared to the stored maximum. The pressure ratio mechanic acts as an analogue control in-game: to register, the ratio has to be above 30 %, but some mechanics (such as acceleration and fire rate) depend on the number, so breathing harder performs the action faster.

To make things easier, we designed the system to automatically calibrate to the user's maximum breath on first run. That is: when the player takes the first breath, and the pressure increases above the idle value, the system registers the maximum pressure reached.

There are cases when the user breathes too hard, for instance coughs or obstructs the resistor valve, and wants to reset the maximum pressure. We provided a menu option of calibrating the breathing device (Fig. 21.8). Here, the user can

Fig. 21.9 The game menu

toggle automatic pressure calibration (so once fixed, the maximum pressure stays fixed) and reset the current settings.

The system is designed in a way that maximum pressure is saved for each user so that, without resetting the game, there is no need for recalibration.

21.4.5 The Cystic Fibrosis Games

To keep a sense of consistency and continue building upon already successful work, we wanted to expand on the themes used in the games from the previous iteration of the project. The previous games were limited and featured simplistic mechanics. While keeping the same theme, we expanded them and created a variety of mechanics and more levels that keep the player engaged for longer periods of time, across multiple sessions.

21.4.5.1 Pirate Quest

The *Pirate Quest* game (Fig. 21.9) focuses on the theme of exploration and item collection. The game puts the player in control of a ship, in a large sea populated by islands, pirate hideouts, pirate ships, sea monsters, floating debris and hidden treasure. The player character is on a quest to find a mythical treasure that can be reached by putting together the pieces of an ancient amulet, scattered throughout the seas. To do this, the player must defend friendly islands from pirates, attack pirate strongholds, find lost treasure and defeat various sea monsters.

The player starts at their base, where they can also return at any time to repair, and have to explore the environment to discover the locations of islands, debris and

Fig. 21.10 The player attacking a pirate island

treasure. They can use the map to see nearby points of interest and, once they uncover the location of islands, they become permanently indicated on the screen. Each friendly island they uncover has a mission for the player, which they must accomplish in order to find the missing amulet pieces which are part of the main story of the game. The missions range from patrolling an area and defeating any pirates they find, searching for lost treasure or defeating a sea monster. There are rocks and debris floating throughout the map which, if hit at high speed, damage the player ship.

Sometimes, pirate ships appear to plunder friendly islands, which the player can choose to defeat. If they do so, they recover the gold stolen from the islands, which they can keep. Should they refuse, the island's gold, which would be given to the player when finishing the quest, would be stolen by the pirates.

Pirate islands are larger, heavily defended, but also full of riches. Should the player attack one, the island becomes hostile and begins to retaliate (Fig. 21.10). Sometimes, pirate ships are called to assist with the defence. These not only fire at the player but also chase after him should they run. The enraged islands lose interest in the player after a while and become neutral again, but they also regenerate their health. If the player defeats a pirate island, the pirates surrender their treasure to him. The island then slowly regenerates both health and gold, allowing the player to attack pirate islands from time to time for increased gain.

The gold acts both as score and as currency in the game. In every new level, the player can spend some of it to upgrade his ship, making it faster, tougher or with more firepower. Because this function was considered too advanced for the target audience, it was redesigned to auto-upgrade, thus if the player has enough gold at the start of a level, he automatically buys the first upgrade available.

Once all the amulet pieces have been collected—in a total of three levels—the player is then taken to fight the game's boss. The fight is challenging but not impossible, as the boss retreats from time to time and gives the player the opportunity to go back and repair the ship at the base.

The game is a top-down adventure in the style of Zelda games. Controls in the game are performed mainly by the breathing device and mouse: clicking the mouse on a position will turn the ship toward it while right clicking will fire the cannon in that direction. Breathing will propel the ship in the direction it is facing. For combat, we decided to eliminate the secondary screen used in the previous game and incorporate it into the main gameplay: sea monsters don't attack, just run away, as do the pirate looters. Pirate patrols and defenders come in range of the player and fire cannonballs themselves. The player ship is much more resilient than the pirates, so defeating one ship at a time is easy. To master combat, however, the player must keep moving and fire at the same time as to avoid the enemy cannonballs. As an additional control, the arrow keys can be used for turning.

The game has an unlimited number of lives, and health is calculated in percentages. Should the player be defeated, he will just be transported back to their base, with low life, and must wait and repair. They lose a large part of their accumulated gold, however, which can be recovered by going back to the place where they were defeated. This way, the player is not severely punished for failure, but is encouraged to avoid it.

Finally, we decided to allow the player to carry on playing after defeating the boss: after the final fight, the player is taken to a new area where they can further explore, fight and acquire treasure. Since most levels in the game are randomly created by populating the map with objects, there is an unlimited number of levels that the player can enjoy, though the content is the same, just the number and positions differ.

Because the game is very complicated for young children, there are a number of tutorial levels at the start where the player is guided to control the ship and interact with the game, and given information about the different objects in each level.

21.4.5.2 Flower Garden

This game creates a very approachable experience that was well suited for younger players (Fig. 21.11). The player selects different coloured seeds with a mouse click and blowing into the PEP device to scatter the seeds around the mouse cursor. To add precision to planting flowers, we provided a dispersal radius: a ring around the mouse cursor that shows what area the seeds might land in. The radius can be tweaked with the mouse wheel, allowing faster dispersal at larger sizes or better precision at a smaller region (Fig. 21.12).

We gave the player freedom when it came to shapes: instead of pre-defined levels, players could choose the shape, from a list of possible ones, select its colour and position it in the garden. If they chose to use a shape, or more (up to a maximum of 3), they would receive bonus points for flowers of the right colour planted in the shapes. However, if their accuracy (that is, the number of correct flowers in a shape relative to the total number of flowers within that shape) was bad, they could not finish the level.

Fig. 21.11 The menu structure

Fig. 21.12 The interface and planting area

To allow even more creative freedom, we gave the players the trowel tool, which could be used to remove flowers. Removing a flower costs nothing, but new flowers have to take its place to keep the same coverage.

The purpose of each level was to fill in the garden as much as possible with flowers. Once the coverage passed the 50 % mark, player could advance to the next one. Should they keep planting and reach 80 % coverage, they could then take pictures of their garden, which would be saved in the game's gallery for future reference (Fig. 21.13). Besides the bonus points for higher coverage, this was a good incentive for children to keep on playing.

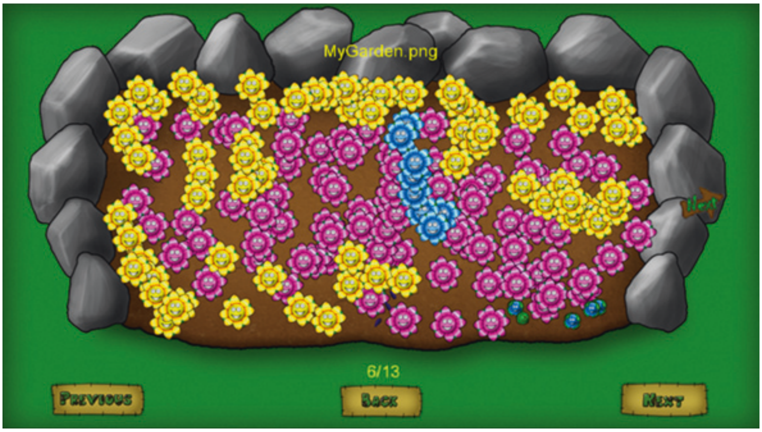

Fig. 21.13 Garden layout saved in the gallery

To add challenge to the game, we kept the limited number of seeds in each sack, but now the players could refill the sack for a price deducted out of their score. Furthermore, we added the possibility to water the plants. Watering makes them grow bigger and have a wider smile, increasing coverage but also giving the player a few extra points. Watering was performed in a way similar to planting: selecting the water can, the player then had to blow in the device and water would pour at the mouse cursor position. Full-grown flowers would shrink back with time, so players had to re-water their garden from time to time.

The water in the can was limited and to fill it, we gave the players a water barrel. The filling mechanic was simple, with the watering can selected, the player has to move the mouse over the barrel and blow to slowly fill the can. Since the barrel capacity was limited, we added a windmill which, when blown upon, slowly pumps water into the barrel.

Finally, we added hungry birds that would occasionally swoop in and eat seeds or flowers. To frighten them away, the player has to select the whistle and blow into it close to the bird, receiving some points for it. He can also plant scarecrows to scare birds away, but this does not receive the extra points.

The wind changes slightly with time and affecting seeds in flight, but because of requests from play testers, we decided to disable it by default. Clicking the wind indicator in the bottom right of the screen re-activates it and grants player more points, but increases the difficulty of planting within the shapes.

The game has an unlimited number of levels, since the mechanics are identical and the score is transferred over to the next one. This way, the player can replay the game as often as they want with the increasing score as an indicator of progress.

We also included a 'Free Mode' level, which includes the planting, removing, watering and filling shapes mechanics, but has unlimited seeds and water to allow the players to freely draw the gardens they wish.

21.4.5.3 Dragon Caves

This game was based loosely on a similar-named game from the previous version of the project. In the last version, the player controlled a dragon in flight through a large cave, blowing into the device to move the dragon and avoid spikes on the bottom and top of the cave. Since the game auto-paused when breathing stopped, players became annoyed at how often the game would freeze waiting for them. Furthermore, having only a limited number of breaths restricted the time they could spend in the game.

To address those complaints, we re-designed the game into an action-adventure genre that has the same side-view platformer style camera, but features unhindered exploration. The basic design was that, instead of one large cave the player had to navigate in the previous version, the level would consist of a maze of small, screen-sized levels that were arranged in random order.

Each level includes traps and enemies that the player must avoid or defeat and collectable items. The purpose of the player is to find the large crystals that power the altars at the end of the level which take the player to the next areas. Initially, the story of the game was that the player, controlling a dragon, is on a quest to bring back the rainbow, which has disappeared from the land, by finding the coloured crystal hearts that must be placed on the respective altars to summon the rainbow back into existence.

The dragon is controlled by either keyboard or mouse for movement and breathing fire, but the primer for these actions is breathing into the device: walking left and right needs only one key press, but to flap the wings and fly, the player need breathe into the PEP device and press the up key (or point the mouse in the vertical direction). The stronger the breath, the faster the dragon rises. Blowing fire also depends on player breath: a higher pressure creates a longer stream of flame while breathing for longer periods of time increases the damage output.

Breathing fire and flying uses up energy, indicated by a bar on the top right of the screen (Fig. 21.14). The player can refill it by huffing (short, powerful breaths) while on the ground or by collecting small crystals. These grow in chunks on the walls in the caves and have to be broken by breathing fire on them. The fire breath slowly heats up the crystal chunk until it explodes into fragments that bounce off the walls. These fragments function both as score and as energy replenishment.

The caves are separated by doors that can be opened with keys: each door requires one key, no matter where it was picked up. The keys are found in some crystals and often dropped by defeating some enemies. To prevent a level from being unfinishable, it is guaranteed that every level contains at least one key.

Some levels contain crystal hearts, which are locked behind doors and feature more traps than normal levels. The end level contains the altar where, if the player has collected all the hearts from the current level, the portal to the next area appears.

Traps are generally present in all the rooms in the maze. There are basic static traps, like the spike trap and spike pit, which harm the player if they step on them—the spike trap has a delay until it is triggered. Other traps feature a moving

Fig. 21.14 A room with a crystal heart and many traps

component, such as the stalactites that fall when the player passes under them, the boulders that fall and roll when the player is near and the lava fissure, where chunks of lava fall out of from time to time.

There are also neutral traps that may help or endanger the player, depending on circumstance. For instance, the steam vent launches the player upward when walking over it, or the wind gust which throws the player left or right when flying through it.

The enemies are slimes that drop out of a pipe and patrol a platform. They damage the player on collision and can be destroyed by fire.

The game also features an editor that can be used to make new levels. These rooms are saved in a folder and used in the creation of new levels, when each room is randomly chosen from the folder of available tiles. This was used during development to facilitate the creation of content but we decided to offer it to players to allow them a degree of creative freedom.

The game provides a tutorial level at the start, where each mechanic is explained to the player. Because the levels are randomly generated from the pool of available rooms, the game has no ending and can be replayed over and over, with new levels generated every time.

21.5 Results

Feedback from the pilot study was from a single player (6 year old CF patient and her family) in play testing. As errors often occurred or features needed rapid tweaking, the tester preferred to use emails to communicate feedback as often as they felt needed. Generally, we received regular feedback (weekly) with the player impressions and suggestions. The tester also contacted us as soon as a problem emerged, as per our instructions.

The feedback was generally unstructured, including impressions, bug reports, and suggestions. We made adjustments based on the pilot feedback, for example,

- The Flower Garden game was well received as the participant played a full 15-min first session before becoming slightly bored. Subsequent sessions, when discovering new mechanics (removing and watering flowers) were more enjoyable. The players focused more on planting flowers accurately and felt irritated by the wind blowing them away. We turned off the wind mechanic by default.
- Calibrating the games felt too confusing for participants as the buttons and indicator were not very intuitive. We changed the calibration menu to make it easier to understand.
- Flying in the Dragon game was considered easily cheated with quick breaths. We modified the mechanic to reward longer breaths with higher speeds.
- Controlling the Dragon and Pirate games through mouse was suggested as this allowed one hand freedom to hold the device. We added a system through which clicking and mouse movement would suffice both games in terms of movement.
- The graphics and cartoony style felt appropriate for the players, though some buttons either had text with little visibility or were not intuitively named. We addressed the issue by changing text and contrast where appropriate.

21.5.1 Control Data

From the control data collected, we can observe that all participants performed at least daily PEP sessions, some with a combination of other airway clearance therapies. It is also observed that some use therapeutic games such as blowing cotton balls.

Most respondents said they perform therapy in late afternoon or evening, sometimes before bed. This seems to be a good schedule as children are sometimes busy with school in the morning. Others perform sessions in the very early mornings too, just before leaving for, or right after coming back from school.

Most sessions last for 10–15 min with some mentioning a time of 20, or even more, up to 45 minutes, depending on current health. Furthermore, some also mentioned an increase in daily sessions when the child is unwell.

21.5.2 Game Statistics

There were a number of erroneous data entries that were filtered out. Possibly due to abnormal session terminations (e.g. quitting games half way through) or Internet connectivity related issues. With the erroneous data filtered out, we can identify trends. However, we realize that this data was from a small number of participants and over a short period of time (two weeks) and are not statistically significant.

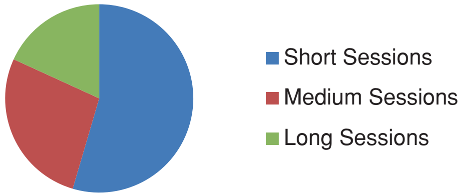

Fig. 21.15 Types of play sessions recorded for the flower garden game

21.5.2.1 Flower Garden

According to both our participants (via the questionnaire) and the collected game data, the most played game was the *Flower Garden*, with 21 total records of play of which only 11 are counted as complete sessions because they lasted for more than a minute. Duration-wise, we can see three types of sessions arising (Fig. 21.15):

- Short sessions, with an average of 3 min 6 s per session (session times being between 1:51 and 5:08 for 6 sessions)
- Medium sessions of 9 minutes 52 seconds average play time per session (with session times being between 9:05 min and 10:36 min for 3 sessions total)
- Long sessions of 21 min 8 s on average (20:53–21:24, 2 sessions)

The number of breaths varies with session time, with an average of 20 breaths for shorter sessions, 88.6 for medium and 275.5 for long sessions.

In terms of the time of day when those sessions were carried out, some sessions took part in the middle of the day, with 8 sessions taking place between 15:00 and 16:00. Unfortunately, these sessions did not produce complete data or had very short durations, indicating either some kind of problem with the games or the data transmission or the players trying to familiarise themselves with the software without engaging with it in the way intended for physiotherapy. From the 11 sessions that produced complete data, 3 took place between 17:00 and 18:00. Most sessions however took part between 21:00 and 23:03. This suggests, as has been indicated by previous research, that evenings just before bed time, is the preferred time for young children and their parents/carers to perform therapy sessions.

21.5.2.2 Dragon Caves

The second most played game was "Dragon Caves", with 20 sessions of play recorded, 7 of which lasted more than a minute.

This was the most played game per therapy session, with an average play time of 22 min 38 s. The amount spent playing the game was recorded as: 2 sessions under 10 min (2:31 and 7:18 min respectively), 3 sessions between 16 and 24 min (16:11–23:41) and 2 above 30 min (33:58 and 58:17).

The number of breaths is small for the short sessions (7 and 33 breaths recorded respectively) but much larger for the others, with the medium sessions having an average of 359 breaths while the long sessions had a similar average number of breaths recorded with an average of 408 breaths. This indicates that more time was spent either paused or in the game's editor in the long sessions. It still shows however that there is a tendency to play this game for sessions longer than 15 min, which is a recommended minimum daily therapy dose.

21.5.2.3 Pirate Quest

The first game we developed was, ultimately, the least played one, with just 19 total sessions and only 10 above one minute, but also with the lowest average session time of just 4 min 27 s (shortest session was 1:07 and longest session was 10:09). The gameplay time breakdown is as follows: there are 4 sessions of less than 2 min of play and with an average of 1:25, 3 sessions between almost 3 and 5 min (2:55–4:16, 3:42 average) and 3 of more than 8 min (8:04–10:09, average 9:15).

The average number of breaths for the short sessions for this game is 30 (12–42) for shorter sessions (under 8 min), while the longer ones have an average of 109.3 (40–151).

The low amount of time spent by players with the *Pirate Quest* may be due to the young age of the players (player's reported age was 5). The relative complexity of the game mechanics may have been more than what the players could handle. This game was the most difficult to play out of the three.

21.5.2.4 Games Questionnaire Data

The questionnaire recorder demographic data, including the names of the patients and their carers, their addresses as well as the hospital details in charge of the patients. It also captured PEP exercise data and in particular:

- The average duration of time per PEP physiotherapy was between 10 and 30 min.
- The amount of times is PEP therapy was performed each day which was between 1 and 2 times. On some occasions more if the patient was unwell because of CF.
- The repetitions of the breathing exercise performed per set which was 10.
- The number of sets performed per session the average of which was 6.
- The time of day that PEP therapy sessions were performed. These were mostly early in the morning and late in the afternoon (typically before and after school).

The questionnaire also captured the following information:

1. On a scale of 1–5, with 1 being very easy and 5 being very difficult, how easy is it to persuade your child to start the PEP therapy? The average score for this question was 2.5. This is for all participants for both weeks of the usability study and for both sessions wherever more than one pep sessions took place.
2. On a scale of 1–5, with 1 being very easy and 5 being very difficult, how easy is it to maintain your child's interest in the PEP therapy throughout the duration of the therapy. The average score for all participants was 3. Somewhat difficult to maintain the child's interest during PEP therapy sessions

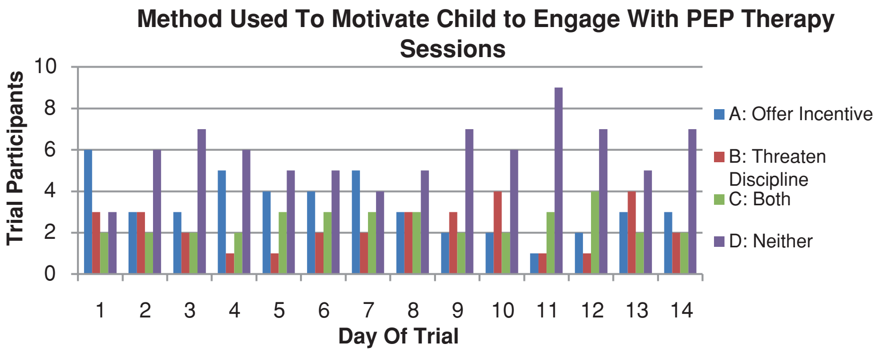

Fig. 21.16 Motivation method for PEP therapy session

3. In order to get your child to engage in PEP therapy did you need to (A) offer an incentive, (B) threaten discipline, (C) both (D) neither. The predominant method of getting the child to engage with PEP therapy was D (neither of the options). The second most popular was A (offer an incentive). Figure 21.16 shows the distribution of methods used to motivate children to engage with PEP therapy over the 14 days of the usability study.

21.5.2.5 Automatically Collected Game Data

In addition to the questionnaire data collected above game data was captured by the system automatically. The data recorded are: *ID, Address, StartTime, EndTime, TimePlayed, Breaths, GameTime, MenuTime, Deaths, Age, Level, Game title, MaxPressure, LongestBreath,* and *AverageBreath*.

The total number of sessions recorded were 719. The total number of sessions completed was 264. The following summaries were produced following analysis of the data.

1. Total time played by all participants: 42 h
2. Total number of breaths by all participants: 14,876
3. Time spent on game menus by all participants: 46 min
4. Total in-game deaths for all players: 152
5. Player average age: 7 years old
6. Player age range: 2–12 years old
7. Highest level achieved in each game:
   Flower Garden: 40; Pirate Quest: 8; Dragon Cave: 6
8. Times a game was played:
   Flower Garden: 87; Dragon Cave: 115; Pirate Quest: 62
9. Maximum breath pressure recorded: 1,023 (software maximum)
10. Longest breath recorded: 16.07 s
11. Average breath duration: 0.9 s

21.6 Data Analysis and Conclusions

The system seems to be successful in its original goal: players, and especially parents and carers, reported that often the children want to carry on playing the game, especially the *Flower Garden*, beyond the recommended 15 min of therapy per session. In games with longer levels, players would like to keep on playing at least until the level was finished. Therefore, it is recommended to keep levels shorter, below the 15 minute mark, compensating with more levels and content throughout the game to keep players interested in coming back.

In terms of the amount of time patients spent playing the game we can see that for the 264 sessions completed (out of a total of 719 sessions attempted) patients spent 42 h in total engaging with breathing exercises. This is in comparison with 49 h of non-games based exercises as reported in the baseline questionnaire. We suspect that the total amount of time patients spent engaging with breathing exercises with the games is significantly higher as we did not present any data for the incomplete sessions (455 in total). The lack of data for these sessions is being investigated as either a technical or data capture design fault and will be addressed in the next version of the software.

It was also surprising to see that although the games were clearly more motivating for children to engage with most carers reported that they did not need to offer incentives or threaten discipline for children to engage with traditional PEP physiotherapy. Still, there was a significant number of cases were both the above methods were used with incentives being the most popular one.

The most popular game seems to be “Dragon Cave”. Contrary to the designers’ expectations that it would be the lease popular (the designers expected *Flower Garden* and *Pirate Quest* to be more popular due to the fact that both had more game content). This is an indication that simplicity is important in designing games for young children and particularly for the purposes of exercising.

It was interesting to observe the longest breath time recorded (at 16.07 s) as well as the average breath duration (0.9 s) and the total number of breaths (14.876). We believe that these data, in addition to the maximum and average pressure data should be useful to physiotherapists and doctors for identifying trends and monitoring a patient’s progress.

In conclusion we believe the study has shown that games based PEP physiotherapy is a desirable, viable alternative that can perform at least similarly to the existing approaches in terms of the amount of time children spend engaging in breathing exercises and with potentially many additional benefits including the capture of detailed data about the amount and quality of physiotherapy which is currently impossible with existing, non-computerized methods. More research is however needed to verify the significance of the results.

21.7 Limitations and Future Work

This section describes some aspects of our project which we feel can be significantly improved and give recommendations for possible future work which use this study as a starting point.

Overall, we were pleased with the design of the hardware peripheral. Using DIY materials and electronics readily available kept the cost relatively down, the device is small and portable for its intended purpose. The current device has a fairly limited sensor range, so there is a possibility of including a better performing sensor. The device could also be coupled with additional extensions, such as the Flutter and Acapella devices for additional gameplay options.

While GameMaker is an excellent platform for fast development of simple games, it lacks the power to create real current generation content: there particle effects are simple, real-time lighting and shadows must be implemented manually and there are no readily-available shaders or advanced graphics functions. It has 3D rendering functions built-in, but the 3D engine is slow and of insufficient quality when compared to other 3D development environments or games such as UDK or Unity.

The future plans for this project include improving the data capturing system so that data are recorded even for incomplete sessions; improving the audio-visual quality of game content and gameplay mechanics to ensure that children remain motivated for a longer period of time; and creating a portable version of the device for mobile and console gaming.

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Chapter 22
Immersive Augmented Reality for Parkinson Disease Rehabilitation

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Abstract In this chapter, an immersive augmented reality system is proposed as an approach to create multiple interactive virtual environments that can be used in Parkinson Disease rehabilitation programs. The main objective of this work is to develop a wearable tangible augmented reality environment focused on providing the sense of presence required to effectively immerse patients so that they are able to perform different tasks in context-specific scenarios. By using our system, patients are able to freely navigate different virtual environments. Moreover, by segmenting and then overlaying users' hands and objects of interest above the 3D environment, patients have the ability to naturally interact with both real-life items as well as with virtually augmented objects using nothing but their bare hands. As part of this work, Parkinson Disease patients participated in a three-week dual task assessment program in which several tasks were performed following a strict protocol. In order to

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assess patients' performance, the tasks were carried out both in the real world and using the system. The findings of this work will help evaluate the viability of using augmented reality as an auxiliary tool for Parkinson Disease rehabilitation programs.

22.1 Introduction

Parkinson Disease (PD) is a progressive degenerative disorder of the central nervous system characterised by a large number of motor and non-motor features that can impact on function to a variable degree. There are four main motor features of PD: tremor at rest, rigidity, akinesia (loss of control of voluntary muscle movements) and postural instability [19]. Gait is one of the most affected motor characteristics. Gait abnormalities can cause loss of balance and a tendency to fall, which often causes serious injuries [1]. In addition, the non-motor symptoms associated with PD include autonomic dysfunction, cognitive/neurobehavioral disorders, as well as sensory and sleep abnormalities [19]. As the percentage of the elderly in the population grows, the prevalence of PD in North America is expected to double in the course of the next 20 years. There is an important economic burden caused by the disease [10]. In the United States alone, the annual economic impact of PD is estimated at \$10.8 billion, 58 % of which is related to direct medical costs [16, 29]. Given the economic impact, the decrease in quality of life caused by PD, along with the predicted rise in prevalence, there is a substantial need for new and novel methods of treatment and rzehabilitation for PD.

Unfortunately, there is currently no cure for PD, but there is medication and various forms of therapy and rehabilitation designed to help manage symptoms and improve quality of life. However, several issues with current approaches to rehabilitation of patients with PD have been reported [23], with the lack of task and context-specific rehabilitation programs being a main issue. Benefits from rehabilitation have been often linked to context, and the in-clinic context is typically contrived or artificial and does not adequately capture real life scenarios, situations or challenges that patients face in a daily basis. Limitations of the in-clinic environment restrict the types of activities that can be made as part of rehabilitation programs [23]. In particular, scenarios that are potentially hazardous or dangerous, yet are part of daily life, cannot be supported in current rehabilitation programs.

Recently the interest in Virtual Environments (VEs) has grown in the PD research community due to the potential that comes through the use of VEs. Different scenarios can be simulated, providing whatever "context" is needed, while bypassing inherent limitations of the current clinic environment and ensuring safety regardless of the scenarios presented. Many different VEs can be created through virtual or augmented reality technologies.

In this work, we created three different virtual environments using augmented reality. These environments allow us to assess patients with PD while they perform dual-task activities. How well the patients perform in those activities will help us evaluate the feasibility and limitations of using augmented reality as a support tool in PD rehabilitation programs.

22.1.1 Augmented Reality in This Context

Augmented Reality (AR) is the visual combination of real-time video streaming and computer generated 2D and 3D imagery. Opposed to the classic *Virtual Reality* (VR) paradigm in which users are immersed in an entirely simulated world, augmented reality allows users to stay connected with the real wold while creating the illusion of being in a different physical location. Furthermore, AR provides users with the ability to see and interact with objects that are not present in their surroundings. According to Azuma et al. [5], augmented reality applications should meet the following three requirements: AR should be the mixture of video sequence and computer generated imagery, AR applications have to run in real time, and virtual objects have to be properly aligned (registered) with real world structures.

In AR, computer generated graphics are overlaid into the user's field of view. For example, graphics can be used to (a) add supplementary information or instructions about the environment, (b) insert virtual objects, (c) enhance real objects, or (d) provide step-by-step visual aids that are needed for the execution of a task. In its more basic form, augmented reality overlays simple head up displays, images or text into the user's field of view. More complex AR applications display sophisticated 3D models rendered in such a way that lighting conditions, shadows casting and the simulation of occlusions appear indistinguishable from the surrounding natural scene. Figure 22.1 shows an example of a common AR system in which the video image is acquired, registered and augmented. In order to register the virtual cereal box in the image, the AR system derives tracking information from the video input. After rendering the registered 3D transformation, the real object can take any other appearance or even be transformed into a completely different object. This type of visualization is a powerful tool for exploring the real world along with added contextual information.

22.1.1.1 Registration and Tracking

In order to appropriately integrate real and virtual information, both the real image and the 3D augmentation have to be carefully combined rather than simply attached together. If computer graphics are generated separately without correctly registering the visible real environment, a favorable visual composition between both types of data may not be accomplished. Providing robust and accurate *registration* is the main technical difficulty that AR systems have to overcome. In AR systems like ours, where head mounted displays are used, registration is equivalent to computing the pose (rotation and translation) of the user's viewpoint.

In AR, image registration uses video tracking algorithms that usually consist of two stages: *tracking* and *reconstructing*. In the first stage, fiducial markers or image features are detected. The tracking step usually employs feature detection, edge detection, or other image processing methods. The reconstructing stage uses the data obtained from the first stage to reconstruct a real world coordinate system based on a camera model and object transformations [39]. Figure 22.2 shows a diagram that illustrates a simple AR system and its components.

Fig. 22.1 A simple augmented reality example. **a** Original video feed. **b** Augmented scene

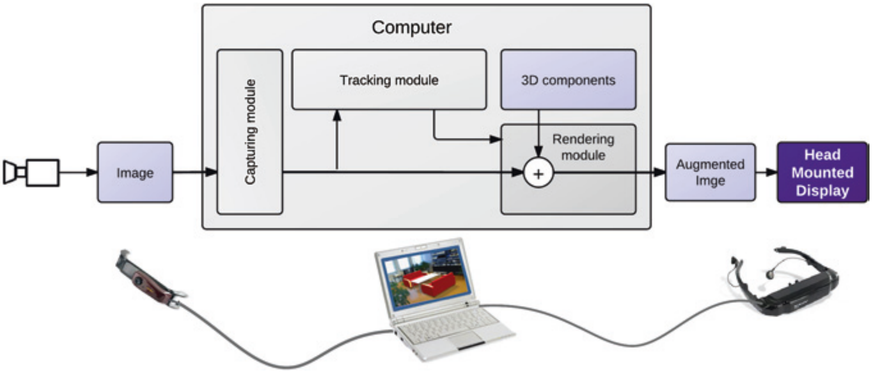

Fig. 22.2 Diagram of a simple augmented reality system

22.1.1.2 The Occlusion Problem and Depth Perception

One of the inherent drawbacks of overlaying virtual environments to video, is that objects of interest are frequently occluded by 3D augmented objects, thus creating an unrealistic effect where foreground items that should appear in front of the augmented information are occluded (see Fig. 22.3). Realistic image composition requires the correct combination between virtual and real objects, in which background/distant augmented objects must be correctly occluded by foreground real objects. Solving the occlusion problem in augmented reality is challenging when there is not enough information about the real world that is being augmented.

If we do not take into consideration the information covered by the overlaying virtual objects, the resulting visualization may cause problems in depth perception. The human cognitive system interprets a set of monocular and binocular cues in order to interpret depth and spatial organization of the 3D objects in the environment, and so we must be careful to simulate these cues accordingly.

Fig. 22.3 Unrealistic effects are created in cases in which augmented objects occlude real objects. In this picture the drawer should be rendered behind the chair

22.1.1.3 Skin Segmentation Using Color Pixel Classification

As mentioned in Sect. 22.1.1.2, in the classic augmented reality approach, what a user sees is a combination of two layers: video as background and 3D as foreground. One of the main challenges of augmented reality is the occlusion problem. In simple terms, occlusion is the process of determining which objects should be visible in relation to other objects. Occlusion provides a very important visual cue to the human perceptual system when rendering data in three dimensions [36].

For example, when we interact with the real world, it is clear that if we place our hand in front of some other object, for example a table, some part of it will be hidden by our hand. In augmented reality systems, occlusion is not always resolved successfully, leading to an unnatural and confusing experience for the user. Skin detection can help tackle this problem by identifying the set of pixels that correspond to skin in an image so that hands can be placed in a separate layer. Thus, instead of having two layers (video and 3D models), we are proposing the implementation of a third layer that would correspond to hands and other objects of interest. With the third layer, the occlusion problem can be corrected by placing skin pixels in front of both the 3D and video layers (Fig. 22.4 shows a representation of the multilayer approach we are proposing to solve the occlusion problem). Machine learning algorithms can be of great aid for computer vision applications such as the implementation of a skin classifier. For this work, we implemented a two-class skin color classifier using an Artificial Neural Network.

22.1.1.4 Presence

In virtual environments, *presence* can be defined as a state of consciousness, the psychological state of "being there" [13, 30]. Witmer and Singer [35], defined presence as the subjective experience of being in one place or environment, even when people are physically situated in another. Involvement and immersion are two concepts of interest related to presence [35].

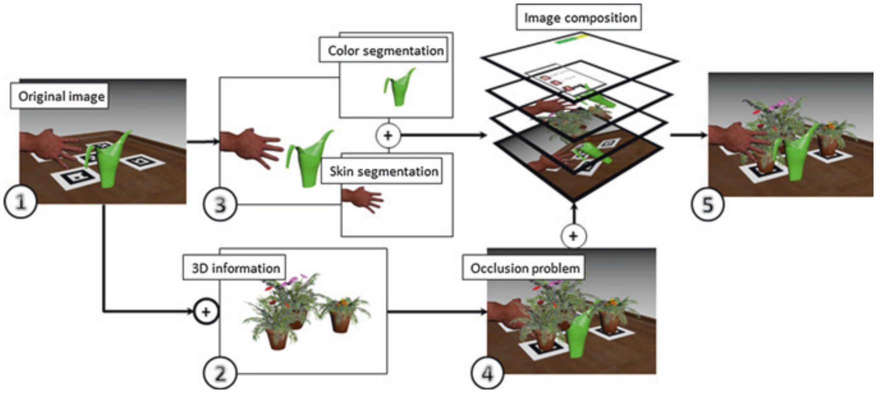

Fig. 22.4 To avoid the occlusion problem (*4*), we overlay the 3D information (*2*) over the original image layer (*1*), and on top of the first two layers we add a third layer composed by the user's hands and other objects of interest (*3*). The result is a properly composed image (*5*)

One of the objectives of this work is to evaluate whether the proposed AR system provides the sense of presence required to virtually transport and immerse users inside the synthetic environment. Based on the work of Witmer and Singer [35], we asked patients with PD to answer a subjective presence questionnaire. The questionnaire was used to evaluate relationships among reported presence and other research variables. The results of such evaluations are described in Sect. 22.5.

22.1.2 Goals of this Work

The main goal of this work is to design, develop and evaluate a wearable augmented reality system, designed to assess patients with PD in dual tasking activities (performing simultaneous motor and cognitive tasks) and assist in programs of rehabilitation. This system will allow patients with PD to interact with both augmented and real objects, using nothing but their bare hands. This approach is novel, because the system provides mechanisms to allow free and natural navigation inside a virtual environment. Through a head mounted display, patients with PD are immersed in 3D virtual environments. In this way, multiple context and task-specific scenarios can be represented. For instance, patients could be immersed inside a virtual environment representing a grocery store, in which they can perform tasks that commonly are difficult to patients with PD. Examples of such tasks are: bending over to pick something from a bottom shelf or walk through reduced aisles while avoiding virtual obstacles. This would allow physicians to observe their patients as if they were present while their patients did their grocery shopping.

The AR system has been used in a series of trials and its performance was evaluated. Those trials followed a strict protocol approved by the University of Western Ontario Human Subjects Research and Ethics Board. Following the protocol instructions, every patient is asked to perform several tasks, both in the real-world and using the AR system. The patients repeat the same set of activities in three appointments during three weeks. At the end of each appointment, they are asked to answer a questionnaire based on Witmer and Singer's work [35]. The results of those questionnaires are used to evaluate if the system provides the sense of presence required for a more intuitive and immersive experience.

22.1.3 Chapter Outline

In Sect. 22.2 of this chapter, we give an overview of related work. In Sect. 22.3, we describe the design and architecture of the proposed augmented reality system. The protocol and method of the study are defined in Sect. 22.4. In Sect. 22.5, we outline the results of trials we conducted to evaluate the performance of the system, as well as the results we obtained from the presence questionnaire. In Sect. 22.6, we summarize this chapter, presenting future work and concluding remarks.

22.2 Related Work

As the main objective of our augmented reality system is to enable novel methods of assessment and rehabilitation for Parkinson Disease, we believe that there is an inherent need to provide intuitive and natural forms of interaction and navigation. In this section, we explore the literature in this area, and examine other applications of virtual environments to the study and treatment of Parkinson Disease.

22.2.1 Registration and Tracking

This section summarizes different tracking strategies used in augmented reality. Non-visual tracking technologies have been used in virtual environments. Active technologies that use magnetic fields or ultrasound are available. Some popular examples of magnetic trackers are the products produced by companies like Polhemus. InterSense produces inertial-ultrasonic hybrid tracking systems such as the IS-900 system. Even though commercial products are robust and provide low latency, they are not widely used in augmented reality due to their high cost. Moreover, they are still prone to errors caused by external factors such as interference. The low cost of video cameras and the increasing processing capacity of computers and handheld devices have inspired a significant increase in research into the use of video cameras as visual tracking sensors. The literature review in this section is focused on vision based tracking methods that have been used in augmented reality applications.

In augmented reality, image registration uses different computer vision methods. Fiducial markers or interest points are detected from camera images. Tracking uses feature detection, edge detection, or other image processing algorithms to analyze live video from a camera. Tracking techniques can be divided in two classes: *feature-based* and *model-based* [39]. Feature-based algorithms consist of finding the relationship between 2D image features and their 3D world coordinates [24]. Model-based methods use real-world object heuristics. For example, a virtual model of tracked objects' features can be used. Another example of a model-based method would be the use of 2D templates based on distinguishable features of an object. Once the relationship between the 2D image and 3D world frame coordinates are found, the camera pose can be obtained by projecting the 3D coordinates of features into the observed 2D image. The reconstructing stage uses the data obtained from the first stage to reconstruct a real-world coordinate system.

Some methods assume the existence of fiducial markers in the surroundings. Other methods, like the one proposed by Huang et al. [15], uses pre-calculated 3D structures for what they call the AR-View. There are two important characteristics of the AR-view approach: the first one specifies that the camera has to remain stationary and the second one dictates that the position must be known beforehand. In their approach, when the scene is not known, they first use fiducial markers and Simultaneous Localization And Mapping (SLAM) to compute the relative position of the device with respect to the scene. In cases where the AR device is static, an approach like the one adopted by Huang et al., can be used. On the other hand, if the AR device is mobile, tracking becomes much more difficult. Movable systems have to be able to model and deduce both camera motion and the structure of scene.

There are some open-source AR libraries available for use, the most popular of which is ARToolKit and its many derivatives. ARToolKit is a library that was developed based on the research of Hirokazu Kato from the Nara Institute of Science and Technology [22]. ARToolkit is a vision-based tracking library that uses real-time video to calculate the camera position and orientation relative to fiducial markers. Once the real camera position is known, the information can be used to correctly overlay 3D computer graphics over the markers.

22.2.2 Natural Selection and Manipulation

Many AR prototypes that support interaction are often based on classic desktop metaphors (for example, a mouse is needed to use on-screen menus, others require users to type on keyboards). Others make use of video game devices and controls such as joysticks, the Wii Remote, PlayStation Move, etc. Techniques popularized by handheld devices such as gesture recognition are also common in AR. The two main trends in AR interaction research are (a) using heterogeneous devices to exploit the characteristics of multi touch displays and (b) integration of the physical world through tangible interfaces [5]. Different devices suit different interaction techniques. For example, a handheld tablet is very useful to play games, surf the web or read eBooks. In augmented reality, users usually manipulate data through a variety of real and virtual mechanisms and can interact with data through projective and handheld displays. Tangible interfaces allow direct interaction with the physical world and virtual world using real, physical objects and tools. Tangible Augmented Reality (TAR) [8] combines the intuitiveness of Tangible User Interfaces (TUI) [17] with the abstractness of virtual objects. In a TAR environment, the user is normally in an *egocentric* view and is able to interact with virtual objects by using a TUI-based direct manipulation artifact. 3D object selection and manipulation is possible by collision or proximity between the prop and a marker representing the 3D object. 3D object position and orientation is modified using a tilting, dropping, or hiding gesture using the prop.

Natural Interaction in virtual environments is a key requirement for the virtual validation of functional aspects in the design of PD rehabilitation programs. For example, in rehabilitation programs, patients are often asked to pick up objects and perform tasks with them. Natural interaction is the metaphor people encounter in reality: the direct manipulation of objects with their hands. As mentioned earlier, our system uses color-based skin classification to segment users' hands from the video signal to allow natural interaction. In our approach, the segmented images are rendered directly over top of the virtual information.

22.2.3 Navigation

The most intuitive way of navigation is natural walking. However, virtual environments still face various restrictions to allow unrestricted walking. One of the big issues of VEs has been the unfulfilled goal of enabling a person to move freely in the cyberspace without using metaphors which translate gestures to motion [34]. Most current setups do not offer the possibility of walking through VEs, or if they do, it is only in a very restrictive manner. In desktop-based metaphors, users simply navigate through the VE using keyboard, mouse or joystick, or similar input devices. This creates a sensory conflict, where the user is physically not moving, but receives visual input congruous with self-motion [31].

Innovative approaches to solve the navigation issue have emerged. Such approaches allow unencumbered movement within the virtual space through user selfmotion. One example is the so called Gaiter System [32], which evaluates the movements of users to simulate motion without using a special floor or treadmills. However the real movement is limited by the room dimensions. The omnidirectional treadmill (ODT) [31] uses orthogonal belts which are made up of rolls. This machine facilitates omnidirectional unrestricted walking in the infinite virtual environment, within a finite real world footprint. A different approach, the Torus Treadmill [6], uses several belts which form a complete torus [18]. These advanced walking devices have usually been combined with Cave Automatic Virtual Environments (CAVE) [11] to maximize the immersive experience.

22.2.4 Virtual Environments in Parkinson Disease Research

Navigation can be seen as an interaction between mobility and an environment that requires the rapid integration of information from visuospatial input, kinematic input and memory. Navigation deficits involving visual processing have been reported in PD [12, 37], and may contribute to gait impairment, increased risk of falls and inefficiency in completing tasks. Virtual Reality is a technology that has been used for assessing and rehabilitating such complex deficits. VR uses computer graphics software to create virtual environments that visually immerse users, resulting in the perception that those environments are "real". Virtual reality has been used in rehabilitation of gait and cognition in a variety of neurological conditions [9, 25]. This technology has demonstrated efficacy for both assessment and treatment [38].

The field of virtual reality research in PD has grown rapidly in previous years. Many studies have utilized non-immersive systems that do not allow ambulation. Studies have focused on aspects of reaching, problem-solving and navigation using non-ambulatory, desktop-based systems [2, 26, 27]. Kaminsky et al. [20] evaluated the effect of visual and auditory cues along with VR to simulate the real-world experience during ambulation. Mirelman et al. [28] used immersive virtual environments to provide visual context and cognitive/motor challenges in a VR gait-training program. However, the trajectory of ambulation was restricted to treadmill walking. Hollman et al. [14], used a curve display and a treadmill to study whether or not gait instability is prevalent when people walk in immersive virtual environments. Their results suggest that the use of treadmills combined with VEs can cause instability in stride length and step width as well as variability in stride velocity.

In a previous in-home VR based project [21, 33], we developed a fully simulated house that delivered visual information in the form of static contextual cues typical of a home environment such as furniture, doorways, walls, etc. In that study, the goal was to observe patients with PD ambulating freely without the inherent veering restrictions of a treadmill in a more "familiar" virtual environment. A head mounted display was worn by patients with PD to visually immerse them inside the virtual environment. Based on patients' orientation and ambulation in the real world, a third person was in charge of navigation inside the virtual home using an experimenter-driven "Wizard of Oz" controlling scheme. A study was conducted with patients with PD and controls in a variety of navigation tasks such as line following tasks and free-form room-to-room navigation tasks. Results from that study were both interesting and valuable, indicating potential for the use of virtual worlds in creating ecologically valid research and rehabilitation environments for PD [21, 33].

Six Degrees of Freedom (6DOF) tracking devices have been used together with VR systems to monitor the position and orientation of selected body parts of users. When used on a head mounted display, the position and orientation of the head can be measured. This information defines the user's viewpoint in the virtual world and determines which part of the VE should be rendered to the visual display. The information delivered by tracking devices can be used to simulate navigation [6]. However, despite their huge cost, tracking devices are still prone to failure due to interference, out-of-range distances, or sensitivity to environmental factors.

Depending on the technology, 6DOF position trackers can be sensitive to large metal objects, various sounds, and objects coming between the source and the sensor.

22.2.5 Discussion

Previously published Parkinson Disease studies have focused on aspects of reaching, problem-solving and navigation. However, patients had to use joysticks or the keyboard to both interact with the environment and navigate through it. In this work, we instead segment the user's hands and make them visible inside the VE to allow natural interaction both with real and augmented objects.

Regarding navigation, researchers have evaluated the effect of visual and auditory cues delivered via virtual environments to enhance the real-world experience and cognitively challenge patients during ambulation using treadmills [28]. Many other non-Parkinson Disease studies have utilized omnidirectional treadmills combined with CAVE systems to immerse people inside virtual environments. Such advanced configurations allow people to freely navigate in any direction inside the VE without restrictions. Unfortunately, the size, complexity, but above all, the price of such systems is so high, that makes it infeasible to use them for rehabilitation. The AR system we developed as part of this work takes advantage of the vision-based tracking characteristics of Augmented Reality to obtain the 6DOF transformation of the camera. We use this transformation to emulate a head motion tracking system. The use of this 6DOF head tracking system allows patients with PD to freely navigate inside virtual environments without using any kind of treadmill or inertial/hybrid tracking devices.

22.3 System Design and Development

As discussed earlier, the main objective of this work is to develop an augmented reality system for Parkinson Disease assessment and rehabilitation that can provide the user with a sense of presence and immersion. We sought to do so without requiring the use of expensive equipment discussed in the previous section. In addition, some technologies are impractical for this particular application. They might not be suitable for in-clinic use, equipment might be bulky, heavy, or awkward for patients to use (especially seniors or people who have mobility issues; for example, treadmill-based systems are not suitable for them). This is important, because our system is intended to be portable and transferable so that it can be used in any clinic without requiring a huge investment. Our system will allow physicians to observe patients with PD as they perform daily life activities in the virtual environment.

Our wearable augmented reality system is transcendental and innovative because it provides natural interaction and free navigation. In terms of navigation, the only limitation of our approach would be the physical space available. This avoids issues found in other work in this area that use desktop-based metaphors, which employ simpler devices such as off-the-shelf game controllers for interaction. In those systems, navigation is implemented through the use of common treadmills. That approach, however, has not given satisfactory results and have been unable to reproduce real-life activities under context, which is very important for a successful rehabilitation. Our system does not suffer these deficiencies because of its design and implementation. In this section, we describe the three main components of our wearable AR framework: the hardware, physical space, and software system.

22.3.1 Hardware

Our approach employs a camera system to sense the environment and provide a source video stream for augmentation and positioning/orienting the user, a computer to run our software and do all the processing involved to construct, compose, and render the virtual environment as the user should see it, and a head mounted display for presenting the environments to the user. The main aspects that we considered for the hardware in our framework were: weight, computing power and connectivity.

The laptop computer. We chose a laptop computer that was light so that it could be fit into a small backpack, as this is what makes our system wearable. Our objective was to minimize the patients' awareness regarding the fact that they are carrying or "wearing" a laptop. We consider this to be crucial to provide a better sense of presence, since the patient can concentrate on the task at hand without worrying about the laptop. Another important factor in our decision was computing power since our system renders 3D graphics and processes video at the same time. In addition, we needed a laptop with support for an Internet wireless connection, video output and USB ports. We chose the ASUS UX31 because it was the lightest Windows-based computer that complied with our requirements. See Fig. 22.5a.

The head mounted display. This device is vital in our system, because it is through it that the user sees the virtual environment in first-person (i.e. as if patients were using their own eyes). Figure 22.5b shows the VUZIX iWear 920VR HMD we are using. This model is light and supports a resolution of up to 1024×768 pixels.

The camera. This device is used to capture video at 30 Hz. The video is processed by computer vision algorithms in order to compute the position of the camera relative to the real world. We decided to use a Dinex CamAR webcam, which is shown in Fig. 22.5c. This model is designed so that it can be easily attached to the VUZIX iWear 920VR HMD.

22.3.2 The Physical Space

In order to use our system, a physical space is required in order to install the fiducial markers needed to represent the virtual world. In this section we will describe the physical setup of the space we used for our experiments.

Fig. 22.5 The three devices used in our framework, (**a**) ASUS UX31, (**b**) VUZIX iWear 920VR, (**c**) VUZIX iWear CamAR

In order to setup our system, the London Health Sciences Center provided us with a room that measures 6.68 m × 4.92 m. The room is enclosed by four vinyl walls over which we mounted fiducial markers. We also installed fiducial markers in the floor. *Fiducial markers* are points of reference that a computer vision system uses to measure the position of the camera with respect to each fiducial marker. The fiducial markers in our system are unique black and white patterns printed on a material known as *coroplast.* Black and white fiducial markers are easier to detect because they provide high contrast. Figure 22.6 shows a photograph of the physical space with the fiducial markers. We installed fiducial markers of different sizes; bigger markers are used to track the position of the camera from long distances, while smaller markers are used so that the user can interact with virtual objects from shorter distances. We used five different marker sizes: 45 × 45 cm, 30 × 30 cm, 20 × 20 cm, 15 × 15 cm and 10 × 10 cm. We installed and configured 110 fiducial markers in total.

As we can observe in Fig. 22.6, the biggest markers, which measure 45 × 45 cm, were installed in the bottom and top of the walls. The reason for this is that both the top and bottom of the walls are farther with respect to the point of view of the user. We can also observe that the markers are smaller in size as they approach the level that corresponds to a person's eyes when looking straight ahead (approximately 1.70 m). In order to compute the position of the camera with respect to the markers in the room, the system must know the 3D position of each marker with respect to a *specific point of reference* in the real world. Therefore, we measured the 3D position of each marker with respect to the point of reference, one of the corners of the room.

22.3.3 Software

In this section we describe the software component of our AR framework. This software is novel because no other Parkinson Disease research has used augmented reality to create immersive virtual environments. Even though our approach to allow natural interaction is simple, users can select and manipulate real and *augmented* objects without the need for external devices. The system was developed to be easy-to-use and intuitive as it is intended to be used by patients with Parkinson Disease.

Fig. 22.6 Picture showing the physical space with fiducial markers on the walls and on the floor

Our system is composed of four main modules: `CoreSystem`, `VideoSource`, `ARDriver` and `ScenarioManager`. Figure 22.7 shows the architecture of our system and illustrates how these four modules interact. As shown in this figure, the `VideoSource` module captures and processes the video signal. The `ARDriver` module computes the transformation matrices of the 3D objects. These matrices are fed to the `ScenarioManager`, which renders the final scene. Each of these four modules will be discussed in the following sections.

22.3.3.1 Core System

The `CoreSystem` module manages the data structures that are used by other modules. In addition, the `VideoSource`, `ARDriver` and `ScenarioManager` modules are instantiated from `CoreSystem`. The `CoreSystem` module also manages the GUI and user actions in general. One of the main advantages of our system is that it allows creating and administering multiple scenarios without modifying or recompiling the source code. `CoreSystem` uses XML configuration files in order to manage the structure and behavior of the GUI and 3D scenarios. Therefore, to create a new scenario, the operator of the system only needs to edit or add to these files without any programming required.

22.3.3.2 Video Source

This module is one of the most important components of our system because it captures the video signal and detects/segments objects of interest such as the hands of the patient. This module is divided into three main functionalities: video capture, color thresholding, and color based skin classification, as described below.

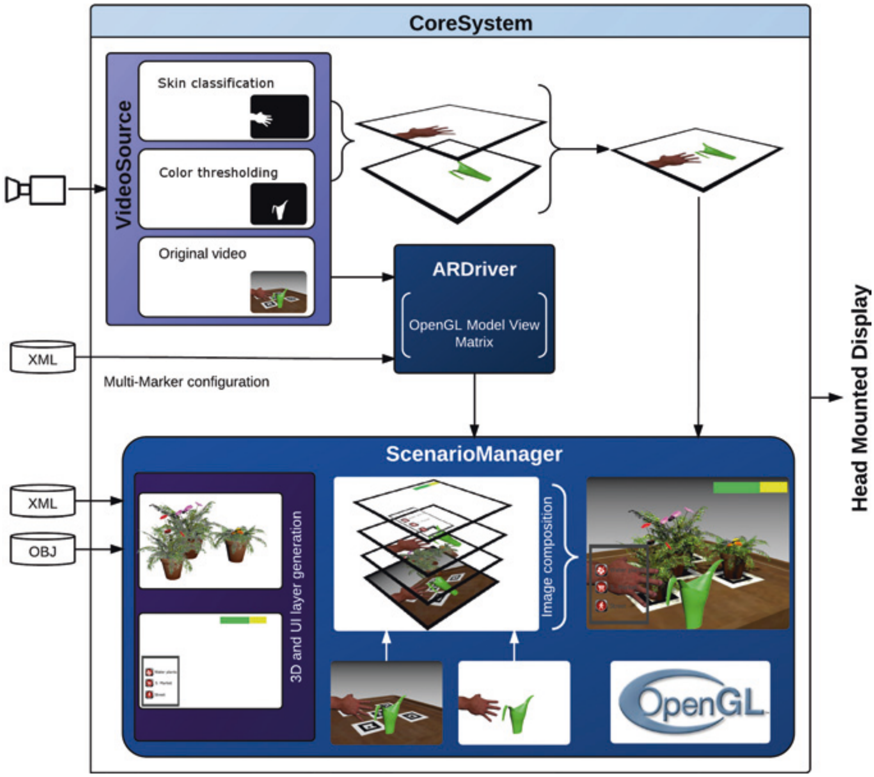

Fig. 22.7 System architecture

Video capture. The captured video signal is sent to the `CoreSystem` module so that the `ScenarioManager` module can incorporate the original video signal as background over which the 3D objects are rendered.

Color thresholding. The `VideoSource` module segments objects of interest using a simple thresholding technique to classify green objects. This classifier generates a monochrome image that is used in combination with the results of the skin classifier to generate a mask which is used by the `ScenarioManager` module.

Color based skin classification. This is the feature that enables the user to have natural interaction with objects in the environment using their hands. We used an Artificial Neural Network (ANN) classifier, because among the other options we tested (Support Vector Machines and simple thresholding), ANN gave us the best experimental results, with an accuracy of 85 % over training and testing data.

22.3.3.3 ARDriver Module

This module detects and extracts the position of the fiducial markers with respect to the camera. `ARDriver` receives an instance of the video signal from the `CoreSystem` module and detects all of the fiducial markers on the current frame.

Each 3D object is associated with a series of different markers. This is known as *multi-marker configuration*. Multi-markers are detected according to the hierarchy defined by the `CoreSystem` module. This hierarchy groups fiducial markers according to size. For example, a given multi-marker might be formed exclusively by four 10×10 cm fiducial markers.

In our system, the multi-marker configurations are defined in an XML file, which follows the format defined by the augmented reality library ALVAR. ALVAR uses this configuration to compute the 3D transformation of each 3D object and the result is translated into the format required by the `ScenarioManager` module.

22.3.3.4 ScenarioManager Module

This module integrates information from `VideoSource` and `ARDriver`, in order to render the final scenario. Essentially, it integrates the video signal, the 3D models and the segmented objects of interest to create the augmented reality environment that the user perceives. In Fig. 22.7, in the `ScenarioManager` box, we can observe an illustration of how these elements are merged. Additionally, `ScenarioManager` renders the GUI when necessary. The `ScenarioManager` renders the scene by performing the following actions:

1. `ScenarioManager` receives the original video feed from `VideoSource` and composes an *initial layer* over which the 3D models will be rendered.
2. `ScenarioManager` receives from `CoreSystem` the list of all the 3D models that need to be rendered.
3. `ScenarioManager` transforms the 3D models with matrices received from the `ARDriver` module, to correctly project the models into a *second layer*.
4. `ScenarioManager` receives an image that contains the segmented user hands (through skin classification) and objects of interest (through color thresholding) from the `VideoSource` module. With this information, it creates a *third layer*.
5. Finally, `ScenarioManager` merges the three layers mentioned above to generate the final scene for display to the user.

22.4 Experiment Protocol

One of the objectives of our work was to evaluate whether augmented reality can be used as a support tool in the development of rehabilitation programs for patients with Parkinson Disease. To that end, we performed a series of experiments that are designed to challenge patients in a similar way as it is done in regular rehabilitation programs. We used our system to observe how patients respond to cognitive, motor and executive-function challenges.

For our initial experiments, eleven participants between the ages 50 and 80 were recruited using a convenience sampling technique from the Movement Disorders Centre at London Health Sciences Centre. Nine of these individuals had Parkinson

Disease (patients with PD), while two of them did not (controls). The criteria for inclusion and exclusion of participants in the trials were determined by the Movement Disorders Program. For example, patients with a high-level of dementia were excluded from the study because they are unable to follow instructions. Patients that present any type of *freezing of gait* were excluded because they are prone to falling. The experiments were performed at the London Health Sciences Centre South Street Hospital. The procedures described below were completed by both patients with PD and controls. The experiments were conducted in 3 sessions over 3 weeks.

In this section, we describe how our experiments were conducted. We developed three different virtual environments. We refer to them as *scenarios*. The first scenario, called "**Watering the Plants**", represents a living room and a kitchen. "**Supermarket**", the second scenario, represents an aisle in a supermarket. The third scenario, "**Street Walk**", represents a pedestrian crossing in a street. We explain these scenarios below.

22.4.1 Watering the Plants Scenario

This scenario represents a room filled with various combinations of flower pots. The flower pots were coloured to different colours and placed throughout this room. In this environment, subjects were asked to move toward a table where there were two rows of flower pots, one on the left and one of the right. They were then given a real watering can. The watering can, as well as the participants' hands, were segmented out to appear in the virtual world. The segmentation and overlaying gives the illusion of immersion and allow natural interaction. The patients were asked, while standing in one spot, to reach and water the furthest plant on the table in front of them, with both their right and left hands, 3 times for each hand. This procedure is performed in the virtual environment first and then in the real world. In the real world, the participant performs the same activity without the visual cues that the virtual environment provides. Figure 22.8 shows a participant performing this task in the virtual environment.

22.4.2 Supermarket Scenario

In this scenario, the participants were immersed in a grocery store in which they could interact with augmented cereal boxes within the environment. One at a time, participants would remove a box of cereal from a shelf in the virtual store and place the box in a numbered augmented basket in the environment. Participants were given a series of numbers to remember representing the order in which baskets were to receive cereal boxes, providing a challenge to both the cognitive and motor skills of participants. The cognitive challenge is memorization. The motor challenge is requiring the participants to bend over, which is particularly difficult for patients with Parkinson Disease. Additionally, this task in particular helped us

Fig. 22.8 Watering the plants scenario: a participant performing this task in the virtual environment

to observe how naturally the participants selected and manipulated the augmented objects. This procedure was repeated 3 times in the virtual environment first and then again in the real world. In the real world, the participants interacted with real cereal boxes and the same baskets that were visible in the virtual counterpart. The baskets were labeled in the same way as in the virtual world. Figure 22.9 shows a picture in which a participant is interacting with the augmented environment.

22.4.3 Street Walk Scenario

This scenario represents an outdoors scene, where the participants must cross the street in a crosswalk to reach a mailbox on the opposite side of the street. The participants must adjust their walking speed based on instructions. The participants are asked to walk in 3 different speeds: normal speed, twice as fast with respect to their "normal" speed and half as fast with respect to their "normal" speed. Participants have to adapt their walking speed based on *internal* or *external* cues. In this context, an *internal cue* is a spoken instruction. An *external cue* is a visual element that indicates how fast the participant must walk. In this case, our external cue is a timer which displays a countdown. The participant must reach the other side of the street before the timer expires.

We measured the time participants took to cross the street using a calibrated stopwatch. Timing began with the first step taken by participants and ended when participants reached the other side of the street. We averaged the results from normal walking speeds in order to obtain what we refer to as a *baseline measurement.*

Fig. 22.9 Supermarket Scenario: The motor and cognitive skills of participants are challenged within this task to observe gait impairment issues

This baseline is our point of reference to define our external cues (i.e. the duration of the countdown). The countdown was defined as half the average baseline (1 *baseline*) for the "twice as fast" trial. We defined the countdown for the "half as fast" trial as double the baseline ($2 \times$ *baseline*). Figure 22.10 shows the outdoors scene with the external visual cue presented to participants. These same procedures were repeated in the real world. This time, in order to represent the crosswalk, we used a mat. Instead of asking the participant to walk towards the mailbox, we asked them to walk towards a red cross marked on the floor. As we mentioned before, our main variable of interest is the time to complete the different tasks. In Sect. 22.5 we will present the results of our experiments. We will analyze whether there was a change in the participants' performance during the 3 weeks of trials.

22.5 Experiment Results

In this section, we present the results of the experiments that we described in Sect. 22.4. Our objective is to measure and compare the time it takes a participant to perform a series of tasks in both virtual environments and in real-life scenarios. If patients take a similar amount of time to perform tasks in a virtual environment with respect to a real environment, augmented reality is not significantly interfering with the patients' perception. Thus, the patients' experience in the augmented world can be deemed similar to the real world. This is an indication that skills learned in an augmented reality environment can be transferred to the real world and that

Fig. 22.10 Street walk scenario: participants have to adjust their walking speed to cross the street in the amount of time that appears in the pedestrian light

augmented reality is adequate for the development of tools that doctors can use to assess or even rehabilitate patients.

Another way of evaluating our system is to determine how participants feel about using our system. For that reason, we asked them to complete a presence questionnaire. The objective of this questionnaire is to determine if our participants perceived our system as realistic. Therefore, this questionnaire is valuable in assessing the suitability of our system as perceived by participants.

To evaluate participants' performance, we focus on two timed scenarios: *Supermarket* (see Sect. 22.4.2) and *Street Walk* (see Sect. 22.4.3). We do not include the results from the *Watering the Plants* scenario (see Sect. 22.4.1), because this particular scenario was not used to measure time, which is our metric of interest here. This scenario was included in the presence questionnaire, however. (Further discussion of the experimental results of this scenario, however, can be found in [7].)

22.5.1 Results of the Supermarket Scenario Experiments

As we mentioned in Sect. 22.4.2, we asked the participants to take cereal boxes and place them into baskets in an arbitrary sequence. This experiment consisted of having patients visit the hospital 3 times (once a week over 3 weeks). In each visit, participants repeated the task 3 times in order to rule out measurement errors.

As trials continued, participant performance steadily increased in the augmented reality environment as the participants adjusted to the environment. During the first visit, the range of times to complete the task was between 25 and 140 s; by the end of the third visit, however, the range of times had been reduced to a range between 22 and 60 s. In real-world testing, on the other hand, performance was much more consistent at between 15 and 50 s throughout all visits as no period of adjustment was necessary. While it took on average 10 s longer to complete the task in the AR environment, accuracy was comparable between AR and real-world testing, with an 81.1 % success rate in the AR environment and 83 % success rate in the real-world, which indicates that there was not a significant interference induced by the AR environment.

22.5.2 Results of the Street Walk Scenario Experiments

As we described in Sect. 22.4, the task in the *Street Walk* scenario consisted of asking participants to walk and adapt their walking speed according to internal and external cues. Using a baseline measurement, we asked participants to walk at two different paces: twice as fast and half as fast (see Sect. 22.4.3).

We observed that participants encountered moderate difficulty in adapting their walking speed using internal cues, but were able to do so more accurately with external cues. While some improvement was seen with repetition, it was not significant. Results were reasonably consistent between the augmented reality environment and real-world testing, with a maximum difference in performance of 5 %. This means that the fact that participants were not able to adapt their walking speed had nothing to do with them being in the virtual environment or the real world. Rather, this result had to do with the complexity of the task in itself. Consequently, we found that for this specific activity, augmented reality is not substantially interfering with the task and that the participants' experience was similar in both cases.

22.5.3 Presence Questionnaire Evaluation

The effectiveness of a virtual environment has been linked to the sense of presence reported by the user. *Presence* can be defined as a normal awareness phenomenon that requires attention and is based in the interaction between sensory stimulation, environmental factors and internal tendencies to become involved [35]. To evaluate if our augmented reality system provided an adequate level of presence enough to immerse patients in the different scenarios, we asked our participants to complete a presence questionnaire after they finished the tasks in every visit. The presence questionnaire we employed is based on the work by Witmer and Singer [35].

The presence questionnaire consists of 34 questions with a 7-point Likert scale, which evaluates different factors that affect the involvement of participants in a virtual environment and thus the level of immersion. These factors can be classified in four categories: control factors, distraction factors, sensory factors and realism factors. *Control factors* refer to the degree of control a user can have when interacting with a virtual environment. In addition, this factor evaluates if a user gets satisfactory feedback to an action. *Sensory factors* refer to how many senses are involved when using a system. *Distraction factors* evaluate whether the hardware interferes with the degree of focus that users achieve. *Realism factors* measure how well the virtual environment is built to simulate real world places.

Overall, we found that participants rated their experience as moderately real to very good and excellent, with an average rating of 5.25 where a score of 1 would indicate the worst experience possible and a 7 would indicate the perfect experience. From this, we can conclude that participants had an overall favorable perception of the system.

22.5.4 Discussion

Our experiments helped us understand the benefits and limitations of immersive augmented reality. Overall, participants had a positive opinion regarding our system, as reflected by the presence questionnaire. Although there was a difference between the time participants took to complete tasks in the *Supermarket* augmented reality environment against the real world, participants were able to successfully complete the tasks *in both cases*. Regarding the *Street Walk* scenario, our results show that the performance of participants in this task was very similar both in the augmented reality environment and real world. Thus, we can conclude that augmented reality was not a factor in the performance of our participants.

We were able to successfully develop an augmented reality system that allows people to freely navigate virtual environments. Moreover, it allows natural interaction with both real and augmented objects. Therefore, this system can be used not only as a support tool in rehabilitation programs, but in other areas as well.

Our system is not without limitations, however. The main limitation is the head mounted display, which restricted the participants' field of view and affected their perception of the virtual environment. Basically, the HMD eliminates peripheral vision. The HMD we used for our experiments provides only 32° of vertical field of view, compared to the normal human eye vertical field of view of 120° [4]. Because this, the current HMD is not suitable for people that suffer from slouched posture as they cannot see important aspects of the virtual world; in some cases limiting them to only seeing the floor of the virtual environment. Another limitation of the system is the lack of physics and collision detection, allowing participants to walk through objects or move physical objects through virtual objects, for example. This would allow participants to employ movement strategies that would not be effective in the real world, which could limit transferability. Both of these issues, however, are being addressed in a new version of the system that is under development [3].

22.6 Conclusions

The main objective of this work was to develop and evaluate an augmented reality system for Parkinson Disease rehabilitation. We successfully developed a flexible augmented reality system that could be used by doctors as a tool to assess their patients. We consider that one of the most important contributions of our system is that it provides users with the ability to naturally interact with objects without the need for external devices. For example, instead of interacting with the system through a mouse or glove, users are able to grab objects with their own hands. This was made possible by our implementation of a skin classification algorithm that allows our system display the users' hands on top of the virtual environment.

Another key feature of our system is that it provides free navigation. That means that users can walk and move freely within the virtual environment, as they would in real-life. Regarding navigation, the only limitation of our system is determined by the physical space where the system is deployed. Free navigation was implemented by using vision-based tracking. This feature allows users to feel as if they were *actually present* in the virtual environment by providing a first-person view.

Another objective of this work was to perform experiments to determine if augmented reality can be used in future rehabilitation applications. Our experiments consisted of comparing user performance in a series of tasks in a virtual environment to the same tasks in the real-world. To perform this comparison, we measured the time it took users to complete a set of predefined tasks. Our results show that the time it took participants to complete tasks in the augmented world is similar to the time it takes to complete the same tasks in the real world. From this, we can conclude that augmented reality provides a realistic environment where users can perform tasks in a similar way as they would do in real life. Also, we found that there is a relation between the sense of presence that participants experienced, and how well they performed in tasks in the augmented environment. This means that if people perceive the virtual environment as being "natural", there are more possibilities to obtain attention and learning that can be transferred to real world activities.

Overall, our research and development experiences lead us to believe that augmented reality can, in fact, be used quite successfully applied in healthcare applications. There is still much work that can be done, however. In order to setup the physical space needed for the system, it is necessary to manually configure all of the fiducial markers to be used. It would be desirable to implement a feature where users could use fewer markers and complement tracking by using natural features to reduce the time needed to setup the system. Such work is already in progress in [3]. We also propose to mix our segmentation algorithms with depth perception and object segmentation to allow multiple levels of occlusion between the real world and the virtual environment. In order to confirm that augmented reality can be used for rehabilitation programs, further experimentation is needed to gather further feedback to improve and refine the system. Such experiments are currently under way.

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Chapter 23
Touchless Motion-Based Interaction for Therapy of Autistic Children

Franca Garzotto, Matteo Valoriani and Laura Bartoli

Abstract Autism is a pervasive developmental disorder characterized by abnormal behaviors along multiple dimensions (socialization, communication, and imagination). An increasing number of technologies devoted to children with autism have appeared in the research arena and the marketplace. Our interest is on interactive tools that exploit *motion-based touchless interaction*, where technology can be controlled using body movements and gestures without wearing additional aides (e.g., data gloves, head mounted display, remote controllers, or body markers). In spite of the increasing popularity of this interaction paradigm, its adoption in therapeutic and educational contexts for autistic children is very limited and research in this domain is still in its infancy. The chapter provides an overview of the current state of the art and describes a field study and that explores the benefits of motion-based touchless gaming for autistic children with low-moderate cognitive deficit, low-medium sensory-motor dysfunction, and motor autonomy. Our findings show that motion-based touchless gaming led to improvements of attention skills for all participants to own study, and suggest future research directions in interactive technology for autistic children.

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23.1 Introduction

Autism is a pervasive developmental disorder characterized by abnormal behaviors that the US National Autistic Society classifies along a triad of dimensions: (1) *Social interaction* (lack of human engagement and impaired capacity to understand other's feelings or mental states, difficulty with social relationships, which results in inappropriate social interactions and inability to relate to others in a meaningful way); (2) *Communication* (difficulty with verbal and non-verbal communication, for example not really understanding the meaning of gestures, facial expressions or tone of voice); (3) *Imagination* (inability to generalize between environments, a limited range of imaginative activities and difficulty in figuring out future events and abstract ideas, which results in difficulty in the development of play capability and tendency to rigid repetitive play behavior).

One cause of the impairments may be the inability to properly synthesize input stimuli. According to some neuroscientists, autistics suffer of a profound abnormality in the neurological mechanism which controls the capacity to shift attention between different perceived signals. This deficit may cause a distorted sensory input (manifested through a lack of fine and gross motor control, and oversensitivity to noise and physical sensations in 80/90 % of children diagnosed with autism). It may also explain the over selectivity in attention to input stimuli that characterize many autistic people [36, 41]. The cognitive inability to recognize and process similarities between different scenes may also account for the lack of imagination and generalization skills. This in turn originates an expressed need for predictability and the related tendency to adopt rigid patterns of action, resistance to change in routine, an obsessive concentration on particular elements or subject area, and a significantly reduced repertoire of activities and interests associated with stereotypical or ritualistic behaviors. Depending on what is included in 'autism',[1] this disorder affects two to five children per 1,000, and has devastating long term effects. As adults, about two thirds of persons with autism remain severely disabled and unable to provide even basic personal care.

In the last years we have seen an increasing number of digital interactive technologies that are designed for ASD children and have therapeutic and educational purposes. Existing market products and research prototypes support a variety of interaction modes and employ different platforms and input devices [33, 34], from conventional mice or joysticks to (multi)touch gestures [20], speech-recognition devices [14, 24], "tangibles" (i.e., digitally augmented objects) [19, 25, 29, 39, 44] or robots [10, 38]. Limited research has explored the potential of "*motion-based*" (or "*full-body*", or "*embodied*") *touchless* interaction [16, 17]. This paradigm exploits sensing devices which capture, track and decipher body movements and gestures while users do not need to wear additional aides (e.g., data gloves, head

[1] Although we use the term "autism" throughout this chapter, people with autism are a very heterogeneous group, and it is more appropriate to use the term *Autistic Spectrum Disorder* (ASD) which acknowledges the fact that autism occurs in differing degrees and in a variety of forms [6].

mounted display, or remote controllers, or body markers). Several authors claim that motion-based touchless interaction has the potential to be more ergonomic and "natural" than other forms of interaction [12, 31, 43]; the gestural dimension resembles one of the most primary forms of human-to-human communication—body expression; body involvement can enhance engagement; the "come as you are" feature removes the burden of physical contact with technology, making the user experience more pleasurable. Theoretical arguments and empirical results suggest that these tools can be beneficial for "regular" children. Still, little is known about whether and how they work for autistic children, because of the limited number of experimental studies and our incomplete understanding of the cognitive mechanisms of these subjects. Hence, our work focuses on some open research questions: "*Is motion-based touchless interaction appropriate for autistic children? Can motion-based touchless gaming help these subject, promote some forms of learning, and be adopted in therapeutic or educational contexts?*"

As a preliminary step to address these issues, we performed an empirical study at a therapeutic center for a period of two and a half months, involves five autistic children and a therapist. We focused on learning benefits concerning the increase of attentional skills (the deficit of which characterizes autistic subjects) and explored several factors in the emotional and behavioral sphere. Measurement procedures included standardized therapeutic tests, observations during game sessions, and video analysis of approximately 22 h of children's activities. Our findings show improvements in the attention level and participants became able to engage in autonomous play in a relatively short time. In addition, positive results were achieved in the emotional sphere.

The rest of the chapter is organized as follows. In Sect. 23.2 we review the most relevant approaches on motion-based gaming for both "regular" and autistic subjects, and motivate our research question in light of the current state of the art. Sections 23.3 and 23.4 present the design of the empirical study and its main results. Section 23.5 draws the conclusions and outlines future research directions.

23.2 Related Work

Studies conducted to consider the effectiveness of digital technologies for ASD individuals reveal that these tools are well received among autistic children [24]. A digital environment provides stimuli that are more focused, predictable, and replicable than conventional tools. It also reduces the confusing, multi-sensory distractions of the real world that may induce anxiety and create barriers to social communication. In addition, digital tools can exploit the benefits of visually based interventions adopted in existing therapeutic practices such as video modeling [2]. Delivering educational contents through digital images, animations, or videos capitalizes on the fact that ASD people are "visual learners", i.e., they learn best through visual means. Most existing technologies for autistic children combine the potential of technology per se with the educational effectiveness of gameplay [6].

Researches show that play is the source for human imagination in young children, and therefore for language development and reasoning [40]. Game-based activities accelerate learning processes, creating a state of flow that promotes attention, increases the capability of selecting relevant information and augments the willing to complete the required tasks. Gameplay is one of the areas of development most significantly affected by the cognitive and emotional impairments of autistic children. Their gaming skills are limited [22]: Integrating digital play into educational routines offers opportunities for encouraging social interaction, developing communication and imaginative thinking, and increasing children's ability to perform a variety of activities needed for daily life.

The potential of motion-based digital play for learning is grounded on both theoretical approaches that recognize the relationship between physical activity and cognitive processes, and a growing body of evidence from psychology and neurobiology. Piaget's theory states that knowledge acquisition arises from active experiences in the world. Embodied cognition theories [45] emphasizes the formative role of embodiment[2] in the development of different levels of cognitive skills. The cognitive processes linked to mastering sensorimotor contingencies originate from embodied experiences; also some higher-level cognitive skills such as mental imagery, working memory, implicit memory, reasoning and problem solving, arise from sensorimotor functions. Recent empirical studies indicate that if learners are forced to gesture, those elicited gestures also reveal implicit knowledge and, in so doing, enhance learning [4]. Embodied cognition provides a theoretical underpinning for the educational potential of touchless motion-based games. This hypothesis is supported by the results of empirical studies that consider regular children and by arguments based on pedagogical practices. Kynigos et al. [26] present a set of collaborative full-body digital games designed to understand what meanings learners develop during body-movement and gestures. Authors report that children perceived body motion as a natural way to interact and mutually communicate, and directly connected their body actions with the mathematical concepts embedded in the games. A controlled study [1] on the relationship between body involvement and engagement in educational motion-based gaming shows that an increase in body movements results in an increase in the player's engagement level, and, in multiplayer conditions, enforces the social nature of the gaming experience. A number of studies [8, 9, 21, 23, 27] discuss the potential of Kinect applications for teaching and learning at school. Kanndroudi and Bratitsis [23] analyse seven popular Kinect games with respect to a set of theoretically grounded learning principles and provide a categorization that can help educators to exploiting this technology for teaching physical, cognitive, emotional and social skills. According to [21], motion-based educational activities can facilitate kinesthetic pedagogical practices for learners with strong bodily-kinesthetic intelligence (who learn better when they are physically involved in what they are learning).

[2] Embodiment is defined as the way an organism's sensorimotor capacities enable it to successfully interact with the physical environment.

The number of works that investigate motion-based touchless experiences for autistic children is limited. The *MEDIATE* project [32] provides an immersive, multimodal and multisensory environment aimed at fostering a sense of agency (the consciousness of being able to exert control over the surrounding environment and obtaining a coherent response) and a capacity for creative expression. Young people on the autistic spectrum are overwhelmed by the excessive stimuli that characterize interaction in the physical world, and tend to withdraw into their own world. Hence the stimuli offered by the MEDIATE system are focused and simplified, yet at the same time dynamic and engaging, capable of affording a wide range of creative behaviors. Evaluations in public settings with more than 90 severely disabled autistic children showed that the MEDIATE environment stimulated curiosity and engagement (the playtime, for example, varied from 5 to 35 min). Pre-post tests administered to 12 children revealed no feeling of discomfort and showed gains in terms of sense of control and agency. Casas et al. [5] describe a Kinect system that aims at promoting the development of self-awareness, body schema and posture, and imitation skills. The system is designed as an augmented mirror where children can see themselves as virtual puppets integrated with virtual characters that behave according to children's movements. In [2], a commercial Wii video game is extended with video modeling capabilities to give the autistic child the opportunity to develop imitative skills during, rather than after, the streaming video footage. The four participants in the evaluation successfully learned to play the game and playing skills generalized to different video-game settings. An attempt of "digital pet therapy" is explored in [7] to improve communication and learning skills of autistic children. The paper describes a Kinect application enabling touchless motion based interaction with virtual dolphins, and proposes a detailed questionnaire to measure the effects on the gaming experience (without reporting any evaluation results). Pirani and Kolte [35] describe a gesture based audio visual tool that is designed to help children with severe language impairments and provides a play-and-learn environment to promote basic skills in arithmetic, spelling, reading and solving puzzles. Other initiatives are announced on the web but are not documented in the scientific literature. For example, the Lakeside Center for Autism in the US [15] integrates Kinect's commercial games into its therapy sessions to assist children with autism in overcoming various difficulties regarding physical and social development. A research team at Nottingham Trent University [18] evaluated 24 young people with intellectual disabilities (including ASD) playing Wii tennis and Kinect Bowling. These gaming experiences taught the students various movements which they could improve upon and mimic in everyday life, promoting skills needed for real world tasks.

In summary, the current state of the art suggests that *motion-based touchless gaming* is associated to various benefits, including improvement of motor skills [15], strengthening of basic cognitive functions such as agency [32] and awareness of self [5], and promotion of engagement.[3] Still, our understanding of the potential

[3] While engagement is considered a *facilitators* of learning processes for regular children, for autistic children it be regarded as a *learning benefit per se*, because of the deficit of these subjects in the emotional sphere and the abnormal way they relate themselves to the surrounding world.

of this paradigm for autistic children remains limited, for a number of reasons. First, most empirical evaluations involve a small number of subjects, with specific characteristics: Considering the heterogeneity of disorders in the autism spectrum, further studies are needed to confirm and generalize the existing results. Second, different evaluation methods are used in the different user studies, which become hardly comparable. Current research offers limited insights on which evaluation procedures are appropriate for this special user group and why, as methodological guidelines in this respect are yet to be developed. Finally, we can hardly establish if motion-based touchless gaming can be effective to achieve learning benefits related to higher level cognitive functions, skills, or competences. In typically developing young children, play routines evolve from explorative to manipulative play to imaginative social responses, forming the foundations of communication, social interaction, and successfully experiencing/understanding the world. Most autistic children do no demonstrate this range of play behaviors [22]. They have strong deficits in spontaneous symbolic play and prefer instead a physical, tangible approach, i.e., playing with objects of interests on a sensory and perceptual level, oftentimes in a repetitive, persistent, and not goal-oriented way. This behavior contributes to explain the positive effects of gaming solutions for autistic children based on robots, smart toys, tangible or touch interfaces, which engage the body and involve physical manipulation of something [9, 42]. Motion based touchless gaming involves physical activity but interaction is intrinsically intangible. Implicit in this paradigm is a “sensory mismatch” between physical behavior and its effects: A body action, e.g., a movement or gesture to hit a ball, triggers a visual or audio feedback, but this effect does not determine all the other sensory and perceptual effects occurring in the real world (the user does not really “touch” the ball). For autistic children, the sensory mismatch might reduce the benefits of embodiment. It may weaken the intertwining of perception, cognition, and action that takes place in “regular functioning” children and is assumed by embodied cognition theories to argue the learning effects of bodily experiences. In addition, interpreting intangible interaction requires some basic abstraction and generalization capability. For example, understanding that you have hit the ball *even if* you don’t experience the bump on your body as you normally do, requires the ability of recognizing and processing similarities between different situations that is typically weak or absent in the autistic child. With practicing, autistic children can become able to correctly perform movements and gestures needed to play a motion-based touchless game. But this effect may account to these subjects’ tendency to favor repeated actions. We do not really know if they build connections at a higher cognitive level and can generalize to different settings or situations the relationship they learned between their movements and the concepts of a specific game.

In conclusion, from existing theory and empirical research on touchless gestural gaming *we do know how this paradigm works for autistic children and which form of learning it promotes for this target*. Any hypothesis is tentative because of the low number of field studies and the limited number of subjects involved, the high heterogeneity of impairments occurring in ADS subjects, the limits of our knowledge on autistic children's cognition and on their way of making sense of the world. The empirical study discussed in the following sections contributes to enrich our empirical knowledge in this field, exploring the benefits of touchless gestural gaming for autistic children in relationship to *attention skills* and various *behavioral and emotional factors* (most of which unaddressed in the current state of the art).

23.3 Empirical Study

23.3.1 Research Variables

Attention is a fundamental cognitive function the deficit of which characterizes autistic subjects (attention tests are some of the first ones undertaken to diagnose autism and its severity [30]). Hence, gaining improvements in attentional skills represents a relevant learning benefits. To our knowledge attention has never been systematically addressed in previous research on touchless gestural games for autistic children. In our study we considered two variables that are proposed in the literature [3, 41] and are measured in the therapeutic practice:

- *Selective Attention*: the capability to focus on an important stimulus ignoring competing distractions.
- *Sustained Attention*: the capability to hold the attention for the time needed to conclude an activity.

We evaluated both variables using a standardized test of visual search, the "Modified Bells Test", adopted in many therapeutic centers in our country. This is a children-oriented adaptation of the method proposed in [11] and consists of a sequence of cancellation tasks. In each task, the child is shown a piece of paper with a clutter of items and is asked to mark as many target items as possible, as fast as possible. Target stimuli (images or shapes, e.g., of bells, with equal size and orientation) are randomly intermixed with different visual stimuli. The evaluation of the attention process is based on the measure of two indicators: accuracy (the total number of target items, identified in the maximum time—normally 2') and speed (the number of target items bells identified in the first 30").

To operationalize the effects of the motion-based gaming experience in the *behavioral* and *emotional* spheres, we considered four variables (Table 23.1): *distress* (the sense of mental or emotional suffering and anxiety), *positive emotion*, *need for intervention agency* (autonomy), *usability gap* (correctness of actions with respect to game logic and interaction rules). Distress is decomposed into finer grained variables (inappropriate movements, negative emotion, overstimulation, loss of attention, loss of interest). All variables are connected with "signals", i.e. observable gestures, movements, or body expressions that externalize feelings, attitudes, or needs.

Table 23.1 Behavioral variables and signals

Behavioral variables		Signals
Distress	Inappropriate movements	genital manipulation, clothing manipulation, teeth grinding, running in place, wobbling, putting hands on the mouth
	Negative emotion	discouragement, jerk, anger, frustration, dissatisfaction, fear, agitation
	Overstimulation	loss of movement control
	Loss of attention	The child looks distracted, “out of the game”, expresses fatigue
	Loss of interest	Verbal or facial manifestation of tiredness; willingness to change the game; attempt to exit from photo galley
Positive emotion		Laughs, smiles, expresses excitation, impatience, exults, jumps, claps, congratulates, chat with the adult
Need for intervention		Adult verbal intervention, adult physical intervention, adult technical intervention, verbal request for help or explanation, verbal expression of incomprehension, confusion
Usability gap		correct movement, prolonged too much, correct movement prematurely done, wrong movement, passive imitation, wrong selection, exit the game, exit the device sensing area, too close to the screen

Variables, sub-variables, and signals have been defined consistently with the practice of the therapeutic centers we are working with to evaluate the appropriateness of a game-based therapy. Some signals are typical of any children; others (e.g., genital manipulation, teeth grinding, running in place, wobbling, and putting hands on the mouth) characterize autistic children and do not have the conventional meaning of normally functioning subjects.

23.3.2 Instruments

The study employed five motion-based touchless mini-games that are commercially available for Xbox 360 Kinect. Kinect is a motion sensing technology, implemented for the Xbox 360 video game console that can sense body movements and identify individual players. Four games belongs to the “package” *Kinect Sports* and one to the package “*Rabbids Alive and Kicking*.”

A therapist, one of the author of this chapter, selected the games after the analysis of over 150 entertainment products. She identified the ones that better correspond to the cognitive and motor level of the children participating in the study using selection criteria normally applied at her therapeutic center for conventional gaming artifacts: (1) task simplicity—all games must comprise one game rule only, so that the children can focus attention and emotions on play rather than on understanding the complexity of multiple game rules; (2) short duration—a game session can be completed in few minutes, to favor concentration (which is very short term in autistic children) and keep physical fatigue at an affordable level; (3) ordering—it must possible to define an order of complexity among the games

Table 23.2 Classification of games

	G1	G2	G3	G4	G5
Resources	Life	Life	Time	Time	Time
Player	Avatar	Avatar	Avatar	Avatar	Self
Task Type	Direct movement	Direct movement	Indirect movement	Indirect movement	Posture

with respect to motor and cognitive skills to engage children in progressively more demanding experiences; (4) balanced diversity—to avoid boredom, the games must have heterogeneous content and design characteristics but they should not be too different to reduce the risk of creating anxiety.

From a game design perspective, the products used in our study can be classified (see Table 23.2) according to the following features defined in [37]:

- resources that can be gained during play: “lives” (the possibility of continuing game play for another round) and “time”;
- virtual representation of the player: “avatar”, i.e., virtual character, or “self”, i.e., realistic or schematized shape of the player’s body;
- task type: “direct”, if a player’s single movement directly affects the behavior of virtual objects; “indirect”, if a sequence of movements is needed to change the game state and achieve a goal; “posture”, if the player must maintain a body posture for a minimum time.

Games are different in terms of digital content and body language, but they share a common meta-structure for the gaming experience (Fig. 23.1). All games involve a configuration phase that enables players to: (1) select a game from the list of those available in a package; (2) choose the play modality—single or multiple player; (3) define the visual characteristics of the avatar(s) that represent the player(s) in the virtual space. At the end of each game, scores and results are shown and children’s pictures are presented (automatically shot by Kinect during play). In the configuration and final phases of *Kinect Sports* games, the player can perform control gestures using either the left or the right hand, indifferently. In *Rabbids Alive and Kicking,* the user must use the right hand for selection and the left arm/hand for the back command. In *Kinect Sports* games, the gesture to select an object on the visual interface is “point your hand to the object and keep it still for some seconds (3–6)”. In *Rabbids Alive*, a vertical movement of the right hand is required to scroll the list of games, and a horizontal movement of right hand in an specific area of the visual interface area to confirm a selection.

23.3.2.1 Game G1: Bump Bash

The virtual environment of G1 is “California Style” beach volley field with palms, skyscrapers, and a big and humorous audience (Fig. 23.2). The goal is to *avoid* da moving ball thrown against the player’s avatar from the opposite side

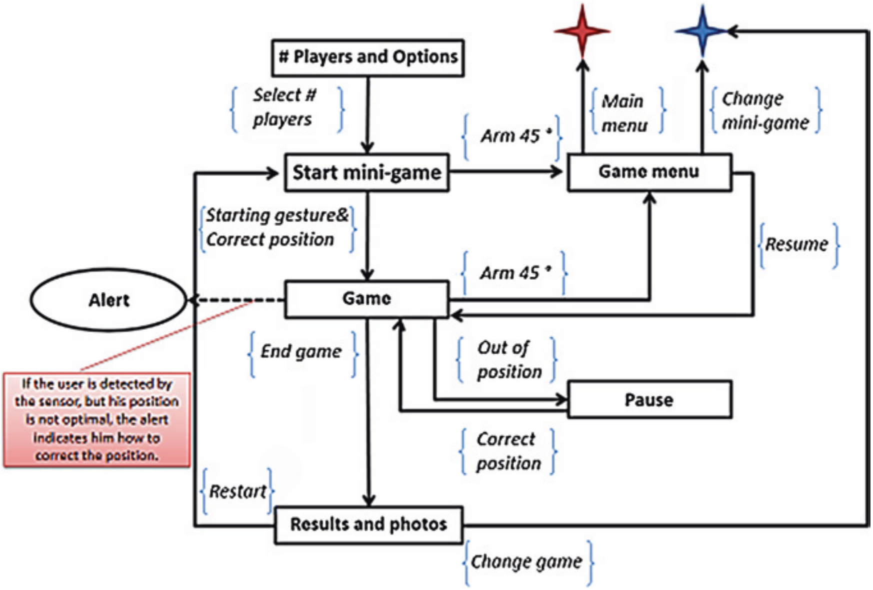


Fig. 23.1 Play experience meta-structure

Fig. 23.2 Game 1 "Bump Bash"

of the field. Red markers on the screen highlight the expected arrival position of the ball. Points are won for each avoided object and contribute to gain extra lives. A life is lost when a ball hits the player. Frequency and speed of balls increases with time.

The game requires (coordinated) movements involving whole body, arms, and legs along the lateral—horizontal body axis. From a therapeutic perspective, it can promote static and dynamic body balance, movement coordination, and attention.

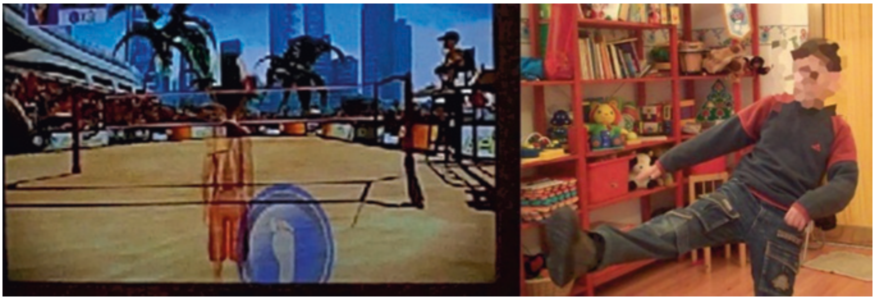


Fig. 23.3 Game 2 “Body Ball”

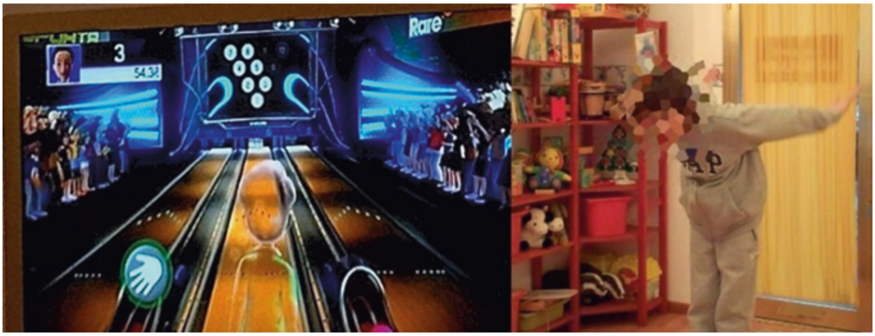


Fig. 23.4 Game 3 “Pin Rush”

23.3.2.2 Game G2: Body Ball

This game has the same virtual environment as G1 but an opposite logic. In G2, the player must *hit* a volley ball thrown from the opposite side of the field to gain points and lives (Fig. 23.3). As the game proceeds, different body parts must be used to hit that are indicated by markers of different shapes appearing on the avatar. Red highlights show the position where the ball is expected to arrive. From a therapeutic perspective, this game requires (coordinated) movements of the whole body (head, arms, legs) along the vertical and horizontal body axes. It is more demanding than G1 in terms of cognitive and motor skills involved. Beside promoting body static and dynamic balance, movement coordination, and attention, the child must understands sequences of stimuli, and plan/organize more complex stimuli-actions patterns.

23.3.2.3 Game G3: Pin Rush

As in real bowling, the player must throw a ball towards a set of distant pins with the goal of maximizing the number of elements knocked over in a minute (Fig. 23.4). Extra time can be gained when all pints are knocked down. The virtual

Fig. 23.5 Game 4 "Target Kick"

environment represents a crowded indoor bowling space, with moving people on both sides of the lane, and many flashing lights. Hand shaped markers appear when a bowling ball is grasped and is being thrown.

From a therapeutic perspective, this game can stimulate eye-hand coordination of multiple body parts at a specific point of time and along the time, as well as goal oriented motor actions, i.e., the cognitive process of organizing movements to achieve a given goal. In addition, this game can promote decision-making skills, as the goal (knocking over as many pins as possible) can be achieved in two ways, using either a single hand to throw one ball or two hands to throw two balls simultaneously.

23.3.2.4 Game G4: Target Kick

This game simulates play soccer (Fig. 23.5). The environment is a soccer field crowded with flags and shouting people. The player must kick the ball towards a target area defended by a virtual goalkeeper. The target area is highlighted by markers that disappear when the area is hit. As the game proceeds, markers become smaller and appear in positions that are more difficult to hit. The game goal is to maximize the number of successful hits in a minute. Extra seconds are earned when all targets are hit within this period.

From a therapeutic perspective, this game involves skills similar to G3, but at a higher level of complexity. Besides promoting static and dynamic body balance, G4 requires eye-feet coordination and problem solving skills, i.e., the capability of building a plan of action and implementing a relatively sophisticate strategy. The child must identify the "best" movement to *both* hit the target area *and* avoid the goalkeeper. In addition, he must understand that if he hits towards one direction, the movement of the goalkeeper will be in that direction, hence the area in the opposite direction will be free, and good for the next kick.

Fig. 23.6 Game 5 "It's not what you think! Honest!"

23.3.2.5 Game G5: It's not What You Think! Honest!

The goal of this game (Fig. 23.6) is to create body postures that mimic closed shapes shown in the virtual world. The child is realistically mirrored on the screen and he must find the correct movements to "fill" the shape, maximizing the area that is "covered" by his body. This activity requires the child to identify the proper body schema and to keep the posture for a while. After 30 s, or when a shape is fully covered, another shape is generated and the task can be repeated. The virtual environment resembles a home bathroom, with the child's body rendered as a shadow on a large bathtub curtain decorated with the shape that must be filled. Fantasy characters—white rabbits—attempt to interfere with the player's activity and disturb him by laughing and jumping here and there. The motor skills involved in G5 are lower than in sport games, but the game is more demanding from a cognitive perspective. G5 aims at promoting the development of self-awareness and self-regulation, imitation skills, and the capability of planning body schema and postures.

23.3.3 Participants, Setting and Procedure

Five autistic boys (hereinafter referred to as C1, C2, C3, C4, and C5) and one therapist participated in the study. Children were selected from a larger group of children attending the afternoon activities at the therapeutic center. Their parents were interviewed, filled a written questionnaire, and gave parental consent. Participants are aged 10–12 and have a comparable clinic profile: low-moderate cognitive deficit; low-medium sensory-motor dysfunction (measured using standard tests, the Developmental Test of Visual-Motor Integration (VMI) and the Movement ABC test [13]); they can perform gross-motor movement autonomously, e.g., to eat, walk, or dress/undress. [15]. No child had prior experience with motion based touchless interaction technology. The therapist had never treated the participants before the study.

The empirical study has been carried on in an ecological setting—the therapeutic center “Associazione Astrolabio” in Florence.

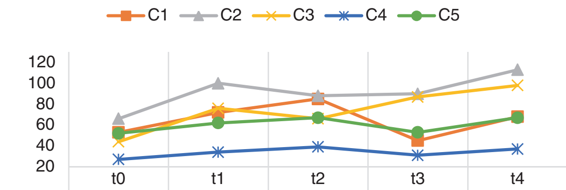
The treatment (approximately 5 h in total) was organized in 6 “*gaming meetings*” (each lasting for approximately 45 min) performed in two *phases*. In phase 1 (“main treatment”), from November 2012 to January 2013, each child attended *five gaming meetings on a weekly base*. In order to progressively increase the complexity of the gaming experience (from game G1 to game G5) and to introduce changes in the play routine, in each meeting the child played with some last used games and with a new one. In phase 2 (“extra treatment”), children participated in a sixth meeting approximately 40 days after meeting fifth and freely played one or more games at their choice. During all gaming sessions, the therapist was sitting or standing aside the child outside the Kinect sensing area, taking notes and intervening when needed. All meetings took place in the same room without modification of the ambient setting: any change of the environment—furniture, objects, equipment arrangement—would be noticed by the child and would create a state of anxiety, introducing confounding factors. No other therapeutic treatment was administrated, at school, home, or at the center during this whole period.

All gaming sessions were video-recorded, using two cameras placed on the wall that simultaneously captured the child’s actions and the game visual interface. Approximately 22 h of video footage in total were collected.

To establish a trend in attention levels, we took attention measures (using the Bell Test) in five different moments:

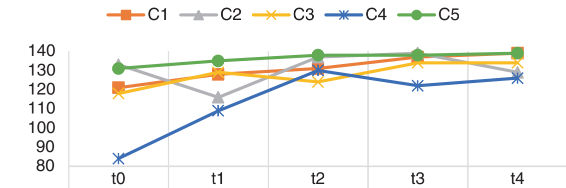
- *t*0, at the beginning of the first meeting;
- *t*1, at the end of the fourth meeting, immediately after gaming;
- *t*2, seven days after the main treatment (during a meeting that did not involved any gaming activities);
- *t*3, *before* gaming at the 6th meeting (40 days after the main treatment);
- *t*4, immediately *after* gaming at the 6th meeting.

There are several reasons why we evaluated each child in specific moments over the study period rather than collecting repeated measures in every session. One reason is that submitting an attention test of approximately 30 min after each gaming session would be tiring and stressing for children; hence we decided to avoid this heavy extra burden. In addition, as autism is often associated with a predisposition for visual memory, reducing the time between test repetitions could create learning effects on Bell Test tasks and introduces a confounding variable. The evaluation at moments *t*2 (7 days after the last gaming session) and *t*3 (40 days after the main treatment) is motivated by the need of assessing the retention of attention benefits along the time. The evaluation at *t*4 (at the end of the 6th gaming session) helped us to establish if the gaming stimulus was still effective after a relatively long period of absence.



	t0	t1	t2	t3	t4
C1	53	72	85	45	68
C2	66	100	88	90	113
C3	44	76	66	87	98
C4	27	34	39	31	37
C5	52	62	67	53	67

Fig. 23.7 Selective attention



	t0	t1	t2	t3	t4
C1	121	128	131	137	139
C2	133	116	137	139	129
C3	118	129	124	134	134
C4	84	109	130	122	126
C5	131	135	138	138	139

Fig. 23.8 Sustained attention

23.4 Results

23.4.1 Attention Skills

Figures 23.7 and 23.8 show the results concerning attention benefits, reporting the attention measures for each child C_i (i = 1…5) in the five different moments of evaluation.

If we compare the values of selective and sustained attention before and after the main treatment (*t*0 and *t*2), we notice *an increase of these variables for all children,* which indicates a *retention of learning benefits in the short term,* i.e., seven days after the end of the main treatment. Concerning *selective attention* (Fig. 23.7), we can observe a *steady* increment for three of the five children (C1, C4, and C5). For two children (C2 and C3) there is a *increment* at the end of the fourth meeting, and a *slight decrease* seven days after the end of the treatment, with values remaining higher than the ones before treatment. We may ascribe the latter phenomenon to the moderating effects of fun: the high level of positive excitement manifested by children immediately after gaming may have increased motivation to perform well during the test.

Figure 23.8 also shows that all children reached a comparable level of sustained attention in absolute terms, in spite of the remarkable individual differences of the measures at the beginning of the treatment. In other words, the overall gaming experience seemed to promote stronger *incremental* results for children with *low* levels of attention skills.

For child C2, the *second* measure of sustained attention (*t*1 values in Fig. 23.8) shows a *decrease* that is fully recovered in the following measures. This effect can be explained by looking at this child's behavior that emerges from video recordings of fourth meeting. While gaming and during pauses he manifested an abnormal number of dysfunctional behaviors and expressed frustration and anxiety. This altered emotional state was due to personal causes outside our control and may have affected his performance during the attention test.

The comparisons of results at *t*2 (after gaming at the end of fifth meeting) with those of before-gaming evaluation in the sixth meeting (*t*3) show that C2, C3, C4, C5 have an increases of both selective and sustained attention while C1 has a decrease in selective attention and an increases of sustained attention. The general trend of values assessed in *t*3 is discontinuous compared to the measures at *t*2, but it is worth noticing that every children obtained a higher score compared to the first evaluation (*t*0) except C1 about selective attention. In the post-game evaluation of the 6th meeting (*t*4) only C2 had a decrease of sustained attention which is slightly lower than the one measured at *t*0. C1, C3, C4, C5 have an increase of selective and sustained attention, showing that the stimulus of the gaming experience is still (positively) active after a relatively long elapse of time.

Overall, our findings are in line with existing studies concerning the positive effects of motion-based games on engagement [1, 6], which in turn is known to create an emotional state that facilitates attention and concentration. Still, we should consider that the relationship between emotions and behavior is hardly predictable in autistic children; a number of user experience variables that are irrelevant for regular children may influence the gaming experience of autistic subjects. Hence our results on attention benefits could not be given from granted and are not "a priori" obvious.

23.4.2 Behavioral Aspects

The psychologist of our team independently analyzed the video recordings of the first five meetings[4] and coded video data using the coding schema (behavioral variables and signals) described in Table 23.1. The results were discussed with the

[4] Video recording of the sixth meeting was not analysed as games were chosen by the children and stimuli were therefore heterogeneous in the different subjects.

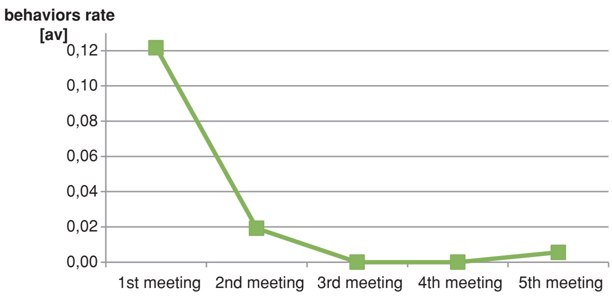


Fig. 23.9 Usability gap measured in the five meetings

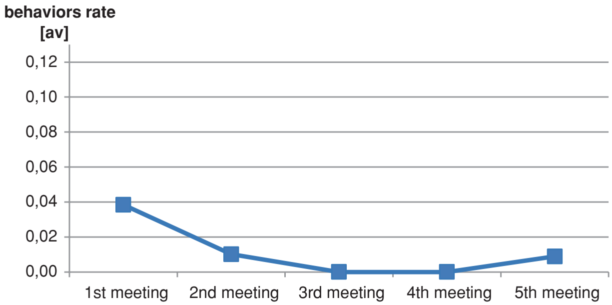


Fig. 23.10 Need for intervention measured in the five meetings

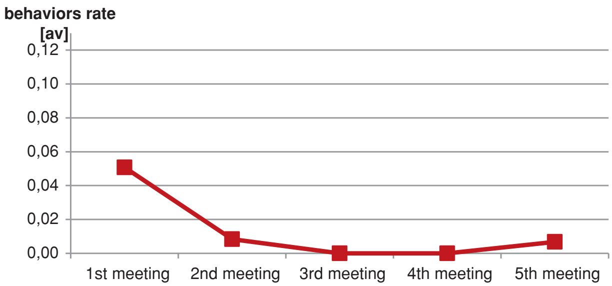


Fig. 23.11 Distress measured in the five meetings

therapist, compared with observations taken during the meetings, and refined accordingly. The analysis of video recordings and therapist's observations pinpoints a number of interesting results. We first consider *Usability Gap, Need for Intervention* and *Distress* in the various *meetings* (Figs. 23.9, 23.10 and 23.11). Then we compare behavioural variables across *games* (Figs. 23.12, 23.13, 23.14, 23.15 and 23.16).

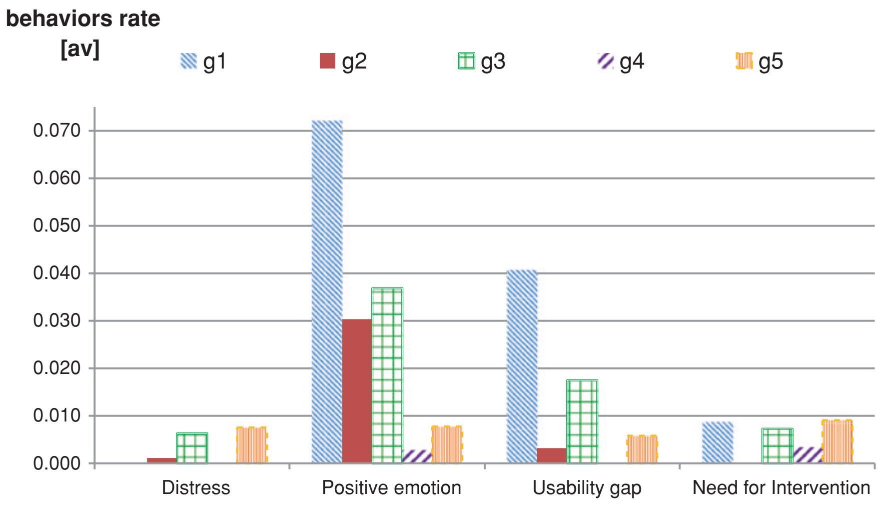


Fig. 23.12 Games comparison: behavioral variables

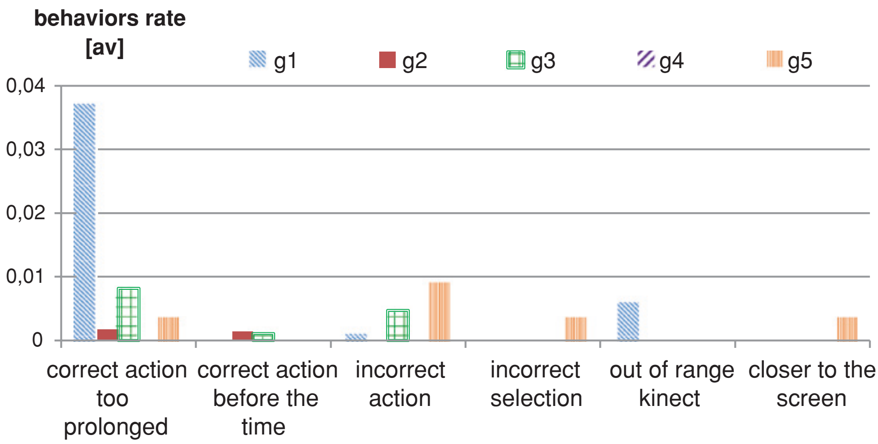


Fig. 23.13 Games comparison: usability gap measures

For each meeting and for each variable in Figs. 23.9, 23.10 and 23.11 values are calculated as the *mean frequency on all children of the signals associated to that variable*. Frequency is defined as *number of signals per second.* For Usability Gap, Need for Intervention and Distress, frequency = 1 is the worst score while frequency = 0 is the best. For Positive Emotion the inverse property holds.

Figures 23.8 and 23.10 show the *progressive decrease* of the *interaction difficulties* (measured by the signals related to *Usability Gap* and *Need for Intervention*) encountered the first four meetings. All initial problems occurred in

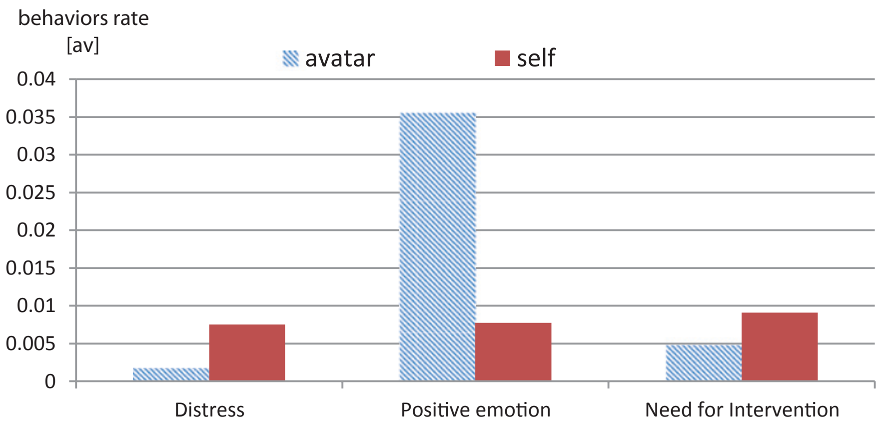


Fig. 23.14 Comparison of behavioural variables between avatar games and “self” games

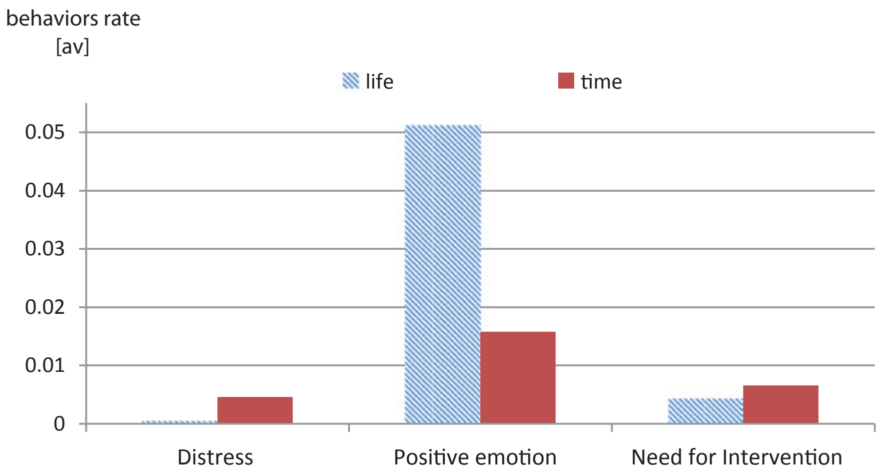


Fig. 23.15 Comparison of behavioural variables between “life” games and “time” games

the first meeting seem to disappear. Coherently, also the *Distress* level *decreases* (Fig. 23.11). After a relatively short time and without any prior experience on touchless motion-based interaction, all children learned how to control the sport games, employed correct movements and gestures, and reached the capability of *autonomous* play, i.e., play without adults’ assistance.

The *increase* of *Usability Gap, Need for Intervention,* and *Distress* is evident in the last meeting, when the Rabbids game was introduced and children were exposed to stronger changes of game logic and design. They had to learn new gestures and to process a larger amount of new visual stimuli and concepts. The increase of the above variables is predictable. Consistently with existing learning theories: when the

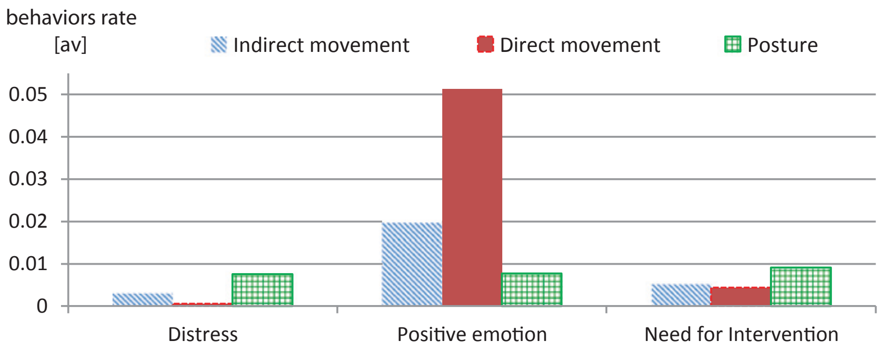


Fig. 23.16 Comparison of behavioural variables among games with different types of movements

available body of knowledge and skills is insufficient to perform a given task, the performance level decreases until new knowledge and skills are built. At the same time, the increment of above variable is relatively small, *certainly not as dramatic as we may expect* from autistic children who normally manifest resistance to *any* change in routine.

Let's now compare the behavioral measures in each of the five games showed in Figs. 23.12–23.16. F*or each variable and for each game*, values are calculated as the *mean frequency on all children and in all meetings of the signals associated to that variable while playing that game*. Figure 23.12 highlights that the values of *Usability Gap, Need for Intervention,* and *Distress* have limited differences across games. G1 (Bump Bash) presents the highest level of Usability Gap. This is not surprising as this game was the first one proposed to children and they had to learn a totally new interaction paradigm. In contrast, the level of *Positive Emotions* is much higher in this game. The later phenomenon may be ascribed to a number of factors: the novelty of the experience (something new creates excitement), the low complexity of the game rule, the simplicity of the movements required, and their dynamic character (children have to run away from the thrown objects). All these elements may have increased fun. At the same time, the "dynamics" factor may have contributed to the increase of Usability Gap, manifested by frequent exits from the Kinect sensing area. Autistic children tend to have impairments in body awareness and difficulties in perceiving the boundaries of their movements in space. The need for highly dynamic full body actions in an unconstrained spatial condition may have emphasized this problem, which could be mitigated, for example, by marking the sensing area on the floor.

Figure 23.13 provides a more articulated analysis of behaviors that indicate Usability Gap. The most commonly encountered signal in all games is the difficulty of interrupting the action "raise hand above head", used to start play. Children executed this movement correctly when asked by the system, but then they tended to remain "tied" to that gesture. Mental rigidity, which determines motor rigidity, is not surprising. A warning on the visual interface that suggests "please withdraw your hand" could be enough to help a child bypass this deficit.

If we analyze the behavioral variables in relationship to game characteristics (Figs. 23.14, 23.15 and 23.16), we notice a *higher* level of *Positive Emotions* in avatar games with respect to "self" games (Fig. 23.14), in life games with respect to time games (Fig. 23.15) and in games that require direct movements with respect to those requiring indirect movements or posture (Fig. 23.16). The result on avatar games is consistent with recent results in autism research [28], according to which children with complex communication needs tend to favor *non-realistic* visual representations of themselves (and of individuals they are emotionally related to).

The result on the more positive feelings associated to "direct movements" games can be justified in terms of the higher simplicity of these games in terms of motor and cognitive skills compared to "indirect movements" or posture games. The higher dynamicity of "direct movements" games may also account for their better results in terms of emotional involvement. This is in line with some findings on regular children [1] that show a relationship between increase in body movement and engagement. The emotional preference for life games is more surprising, as the concept of "more lives to play" sounds more complex than "more time to play", and deserves further investigation.

23.5 Conclusions

While several authors assume that embodied touchless interaction can improve skills of autistic children, the mechanism is not clear and whether touchless gaming is appropriate with these special users is a challenging research question. This chapter contributes to a better understanding of this open issue. The findings of our study provide some empirical evidence that motion-based touchless games can promote attention skills for autistic children with low-moderate cognitive deficit, low-medium sensory-motor dysfunction, and motor autonomy. In a relatively short time the participants to our study could learn how to use touchless gestures to play and could become autonomous players; as the gaming experience proceeded, stronger positive emotions were triggered and distress tended to decrease, moderating the negative effects that "breaks of routine" normally induce on autistic children. After two months, gaming stimuli remained effective and benefits were retained. Still, we don't know the degree to which the measured benefits represent a persistent achievement and what we have measured in a specific setting can be translated to other contexts and moments of participants' life.

Our research design has some flaws, as five different stimuli were given in a series, without returning to a baseline measure. The causality of the improvements is hard to define, as we could not isolate all variables that may intervene in the learning process. We cannot conclude that the benefits we detected have to be ascribed to the motion-based touchless interaction paradigm, the contents of games and their visual design, or a combination of these and other factors. Even if no other therapeutic treatment was administrated to our children during the study period, other activities that the children experienced in these 4 months could have influenced our evaluation. Finally, our work involved five children only—a small sample, but comparable to the sample size of most existing research addressing autistic children's in relationship to technology, and quite a standard number in applied behavioral research. Considering the wide range of ADS impairments, more research is needed both to confirm our results for subjects having profile a similar to the subjects involved in our study, and to translate our findings to other types of autistic children.

All our results have to be considered preliminary and tentative. We are planning new empirical studies in cooperation with a number of therapeutic centers and research institutions in different countries in the context of two EC funded projects. In spite of its limitations, the research reported in this paper sheds a light on how autistic children behave when engaged in motion-based touchless gaming. It is a first step in an exploratory process for identifying how to design motion based touchless playful experiences for autistic children, and how to use them for therapy and education.

Acknowledgments This work is partially supported by the European Commission under grants "M4ALL-Motion Based Interaction for All" (# 2012-3969-531219—Life Long Learning Program 2012) and "Playful Learning on The Cloud" (#SSP13049 EIT ICT LABS Program 2013). The authors are grateful to the children and families from Associazione Astrolabio who participated in our study. We thank Dr. Rivarola from Centro Benedetta D'Intino in Milano for her valuable insights.

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Part VI
Virtual Healing and Restoration

Chapter 24
Virtual Natural Environments for Restoration and Rehabilitation in Healthcare

Robert Stone, Charlotte Small, James Knight, Cheng Qian and Vishant Shingari

Abstract For over two decades, research and clinical projects have exploited Virtual Reality technologies in the treatment of numerous human conditions, from desensitisation régimes combating phobias to the use of distraction and exposure therapies for burns victims and those suffering from post-traumatic stress disorders. In contrast to previous "high-tech" interface and combat-oriented approaches to using VR in the psychological rehabilitation process, the present chapter advocates the use of *virtual restorative environments* (VREs)—the recreation of locations and scenes that, by virtue of their natural beauty and peacefulness, can significantly help to reduce the body's reactivity to stress and restore cognitive or attentional capacities. The chapter also argues that VREs, suitably enhanced with more interactive and dynamic features, could offer significant benefits to patients in physical rehabilitation programmes. This is especially the case for amputees, for example, who, whilst awaiting the fitting of prosthetic limbs, could undertake competitive and motivational "virtual exercises", thereby avoiding muscle atrophy and related reductions in residual limb capabilities. The report concludes that the exploitation of simulation technologies in psychological therapies is worthy of continued investigation, especially in the pursuit of enhancing patients' recovery profiles following surgical procedures, from intensive care to the hospital recovery ward. VREs possess a range of important qualities, not least significant of which is *real-time* interaction and ease-of-editing, supporting the cost-effective generation of engaging and distributable scenarios that can be tailored relatively easily to meet the needs of individual patients.

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24.1 Introduction

Since the early part of the 1990s, when Virtual Reality (VR) technologies made their inaugural appearances on the world's information technology stage, there have been many attempts to develop a wide range of interactive 3D solutions to support medical and psychological interventions (e.g. [60, 62]). Even with the "fall from grace" of VR in the late 1990s and early 2000s (e.g. [58, 59]), the one application domain that has survived throughout—as conferences, dedicated journals and professional societies bear witness—is that of clinical, surgical and psychological medicine.

As well as the early interest demonstrated during the 1990s in developing VR systems to support medical training and interventional planning (e.g. [20, 55, 62]), many institutions, notably universities in the United States (US), began to focus on the power of VR to support psychological therapies. VR could, it was argued, effectively present patients with controllable, simulated—sometimes even fantasy-like—realities, whilst they were present in the safe setting of a therapist's office or clinic. This was in stark contrast to exposing patients to real-world, potentially threatening environments, where a multitude of uncontrollable sights, sounds, smells and events could "flood" the patient with undesirable experiences. From the early 1990s, through to the early 2000s, and despite the still-primitive and costly nature of the VR equipment available, large numbers of research and clinical projects were undertaken, with applications in treating:

- acrophobia (fear of heights; e.g. [41, 53]),
- claustrophobia (fear of confined spaces; e.g. [5]),
- agoraphobia (fear of open spaces; e.g. [42, 43]),
- glossophobia (fear of public speaking; e.g. [45, 47]),
- arachnophobia (fear of spiders; e.g. [8, 21]),
- aviophobia (fear of flying; e.g. [35, 44]).

24.1.1 Distraction Therapy

One of the more powerful examples of applying VR technologies in support of a therapeutic process is that of distraction therapy in pain management and control. Distraction therapy refers to the use of non-pharmacological techniques designed to reduce the onset or severity of an anxiety attack or other stressful/painful situation. The success of distraction therapy is based on the extent to which a patient's limited attentional resources can be "channelled" away from the conscious perception of pain by using alternative forms, and optimum levels of sensory stimulation—visual, auditory, haptic (force/touch), proprioceptive (joint position and motion), even olfactory (smell). The use of VR in this context is appealing, as the technology has always offered the potential to deliver a range of multi-sensory distraction techniques, courtesy of the numerous (and ever-evolving) forms of interaction and display devices available on the commercial off-the-shelf (COTS) market.

A highly publicised and oft-quoted example of a successful VR distraction therapy system is *SnowWorld*. Developed by Hunter Hoffman, David Patterson and colleagues at the University of Washington's Human Interface Technology Laboratory (HITLab) in Seattle, burns victims can, by wearing a head-tracked VR HMD, navigate their way through a simulated "ice canyon" populated with virtual snowmen, penguins and igloos. Their task is to shoot snowballs at these virtual targets, with the illusion of "cold" being enhanced further by the simulated sound effects, which include the sound of snowballs splashing against the canyon sides, or into the representation of an "icy" river. *SnowWorld* is based on the premise that, by capturing patients' attention in a dynamic VE characterised by strong visual simulations of snow, ice, freezing water and other "visually cold" features, they have less available mental or conscious resource to bring to bear on the processing of pain signals (e.g. [25]). Indeed, functional magnetic resonance imaging (fMRI)—a procedure that measures brain activity by detecting associated changes in blood flow—has, in further studies by Hoffman's team, confirmed their hypothesis that "Virtual Reality analgesia" can, in the case of *SnowWorld* at least, be effective in suppressing pain-related activity in five known regions of the human brain. In some cases, participants (healthy volunteers who were subjected to "tolerable" thermal pain stimuli) showed a greater-than-50 % reduction in pain-related brain activity whilst interacting with *SnowWorld* when compared to a condition of no exposure [28].

Another study addressing the use of VR in burns therapy was conducted by Sharar et al. [56]. In their investigation, 88 patients (aged between 6 and 65) formed the participant group. All required post-cutaneous burn passive "Range-of-Motion Physical Therapy" (ROM PT) delivered in sessions lasting 3–15 min. ROM PT is undertaken to help preserve the motion capabilities of a patient's limbs, to help regain their strength and endurance, and to prevent pronounced, raised ("hypertrophic") scarring and the tightening of skin around the wound. Comparisons were made between groups receiving standard pain control (e.g. opioid and/or benzodiazepine analgesics) and those receiving analgesics plus VR distraction using an HMD. Based on self-reported subjective pain ratings (using a scale of 0–100), the addition of VR as a distraction technique resulted in significant reductions in pain ratings for worst pain intensity (20 % reduction), pain unpleasantness (26 % reduction) and time spent thinking about pain (37 % reduction). 85 % of the participants reported no nausea when using the HMD. Children (75 % of the participants, aged between 6 and 18) reported higher sensations of "presence" within and realism of the virtual environment than did adults, but age did not affect the analgesic effects of VR distraction.

24.1.2 VR and Imaginal Exposure

The treatment or management of phobias and related psychological conditions will often use imaginal therapy or "imaginal exposure" in the early part of the counselling process. *Imaginal exposure* is a technique used extensively in cognitive behavioural therapy (CBT, e.g. [54]) and requires the client to describe their traumatic event, step-by-step and repeatedly, to the therapist or counsellor. Alternatively, therapists may actually talk patients through a stress-eliciting scenario. Fear-of-flying sessions held at Royal Air Force (RAF) Brize Norton, for example, have, in the past, used imaginal exposure as part of the treatment with phobic patients (lying down with eyes closed), with the therapist verbally describing the approach to an aircraft from the departure lounge, emphasising the sights, sounds and smells they might encounter as they get closer to, and actually board the aircraft.

CBT is based on the premise that most psychological problems, including post-traumatic stress disorder (PTSD), are linked to significant negative learning (or cognitive) experiences, affecting one's ideas, mental images, beliefs and attitudes. Avoiding remembering such experiences—including exposure to actual or similar places, objects and sensations (even via television, radio and newspaper coverage)—drastically affects the behaviour and day-to-day well-being of the individual concerned, not to mention longer term health prospects (e.g. [9, 19]). Of course, not all patients respond to imaginal exposure, despite agreeing to undertake the approach at the outset. Some are simply unable to control their senses and emotions during the imagination process. Unfortunately, research suggests that, without strong emotional engagement, a poor treatment outcome will often result (e.g. [29]).

One might hypothesise then, that, by exploiting multi-sensory VR simulations (typically visual, auditory, haptic and olfactory) it may be possible to create convincing and engaging simulated contexts to enhance the imaginal exposure process significantly (e.g. [26, 27, 70]). Indeed, in contrast to traditional imaginal exposure and CBT, some research has already suggested that phobia sufferers may be more likely to *seek out* and complete their courses of therapy if VR is part of the therapeutic process [22]. Difede and Hoffman [15] report a single-participant case study—a 26-year old female who was treated for acute PTSD and major depression using VR exposure therapy following the attacks on the World Trade Center Towers in New York on 11 September, 2001. The patient's avoidance behaviours were quite extreme and included blocking out thoughts of the incident, avoiding newspapers and radio or TV reports, even refusing to stay at her partner's high-rise apartment. She had not responded to conventional imaginal exposure therapy. Using an HMD to display images and sounds of the Twin Towers being attacked and collapsing, the patient attended six VR exposure therapy sessions, rating her severity of distress several times during each session using the Subjective Units of Distress Scale [73]. Difede and Hoffman also report that, after the VR treatment sessions, the patient no longer met the criteria for PTSD, major depression, or any other psychiatric disorder, as judged by an independent clinical assessor.

Five years later, Difede et al. [14] evaluated VR exposure therapy for World Trade Center attack survivors with PTSD by comparing the outcomes of a group of ten recipient patients with those of a "wait-list control group" of eight participants. A wait-list control "group paradigm" is a pseudo-control group of participants who provide an untreated comparison for the active treatment group, but are offered the opportunity to obtain the same intervention at a later date. The VR group demonstrated a statistically and clinically significant decrease in scores on the Clinician Administered PTSD Scale (CAPS) relative to both pre-treatment ratings and to those of the wait-list pseudo-control group. Seven out of the ten participants in the VR group no longer carried a PTSD diagnosis, whilst all of the wait-list controls retained the diagnosis following the waiting period. Five of the ten VR patients had previously participated in imaginal exposure treatment with no clinical benefit.

24.1.3 VR and Combat-Related PTSD

Another (highly publicised) application of VR exposure therapy relates to the use of the technology in therapies for treating PTSD in armed forces personnel returning from operational duties. Rizzo et al. [51, 52] report on the use of a well-established VR exposure therapy tool called *Virtual Iraq* (more recently a similar set of *Virtual Afghanistan* scenarios have been developed). *Virtual Iraq* consists of a range of scenarios, including a Middle Eastern themed city and desert road environments. The *Virtual Iraq* system represents quite a "high-tech" solution in the treatment of PTSD, in that, as well as the visual stimuli presented via a COTS HMD, spatial audio, vibrotactile and olfactory stimuli can also be displayed to the patients. The virtual scenarios and stimuli can also be modified in real time, via a clinician-controlled *Wizard-of-Oz* interface (in this case a tablet-like terminal that allows the clinician or experiment to trigger pre-programmed events within that simulation as and when required, such as explosions, enemy fire, appearance of humans, animals, vehicles, and so on), whilst in audio contact with the patient. This interface is instrumental in, as the authors describe it, helping "to foster the anxiety modulation needed for therapeutic habituation".

It is worth noting that the use of VR in the treatment régime described by Rizzo and his colleagues did not occur until the fourth of the ten sessions with the clinician (held twice-weekly, for 90–120 min periods over 5 weeks). The early part of the treatment included clinical interviews, "psycho-education" relating to trauma and PTSD, general stress management techniques, instruction on the use of the Subjective Units of Distress Scale (as mentioned earlier) and a short (25-min), informal introduction to the *Virtual Iraq* VE, without any form of trauma trigger stimuli being introduced. In the actual VR sessions, patients were requested to recount their trauma, as if it were happening again, giving as much sensory detail as possible.

In addition to a battery of subjective measures, physiological monitoring [heart rate (HR), galvanic skin response (GSR) and respiration] was also conducted as part of the data collection. Initial analyses of results from the first 20 *Virtual Iraq* treatment completers (19 male, 1 female, mean age of 28) have indicated positive clinical outcomes. Of the twenty VR treatment completers, 16 no longer met PTSD diagnostic criteria at post-treatment, with only one not maintaining treatment gains at a 3-month follow-up appointment. The authors of this study also reported challenges with dropouts from the sample of active duty participants, seven of whom failed to appear at the first session. In addition, six dropped out prior to the formal VR exposure therapy trials at session four and seven dropped out at various times thereafter.

24.1.4 Human Factors Issues of VR for Exposure Therapy

One of the main reasons for turning to VR or games-based technologies to support psychological therapies is the claim that patients or clients can be "immersed" within realistic simulations of incidents leading to trauma, with the "emotional intensity" of the traumatic scenes being "precisely" controlled by the therapist [51, 52]. There are a number of problems with these claims. Firstly, despite the hype evident in the VR and gaming communities, true "immersion" in virtual scenarios is simply not possible using today's technology. This limitation is set to continue as long as it remains necessary for end users to have to don cumbersome, low-resolution, narrow field-of-view HMDs and use input devices that do not support intuitive human movements or gestures. Indeed, some psychologists question the use of these and related VR technologies (including CAVEs—Cave Automatic Virtual Environments) in the first place, as the use of so-called "immersive" equipment to "exclude" clients from the real world, not to mention issues of cost, poor reliability and usability (see Stone [59, 61], for example), may cause as many problems with some users as it solves.

Putting to one side another concern of some psychologists relating to the appropriateness of "shoot-'em-up" combat recreations, the "precise" control and real-time update of the content of the traumatic scenes is also not possible, certainly not at the tempo psychotherapists might demand. The use of the *Wizard-of-Oz* interface described earlier in Rizzo et al. [51, 52], enabling clinicians to invoke events via a tablet computer linked to the simulation engine has been reasonably successful. However, these events tend to be pre-programmed, generic simulation "vignettes", as opposed to subtle, client-specific, client-relevant experiences.

Finally, there is a concern amongst some defence psychologists that it is impossible to capture all of the objective events that may lead to the triggering of an individual's personal PTSD experience. It is also considered impossible to stimulate—by artificial means (including simulation)—all of the psychological responses manifested by any one individual to these events. Even if one had all of the programming and technical resources of a very large commercial gaming organisation, the production of a highly client-specific simulation within a week or two of an initial psychotherapist referral would be a huge challenge, not to mention prohibitively expensive. This conclusion was also reinforced during early research conducted within the United Kingdom's (UK) Human Factors Integration Defence Technology Centre (HFI DTC), where the time taken to create even the most basic of *Virtual Iraq* or *Virtual Afghanistan*-like scenarios with recognisable United Kingdom (UK) assets and five scenes of increasing "threatening stimuli" (see Fig. 24.1 and Case Study 4 in Stone [61]) was considered to be prohibitive (not to mention potentially costly). More recently, it has been possible

Fig. 24.1 Virtual Afghan village scenario developed for pre-deployment IED awareness training

to develop quite high fidelity virtual scenarios (such as an Afghan Village used for pre-deployment improvised explosive device awareness training; see Case Study 18 in Stone [61]). However, even this development (without dynamic effects or avatars, vehicles and so on) took 4 weeks to complete—a timescale that would be inappropriate for most, if not all UK PTSD referrals.

These and related concerns have prompted the author and his UK research team, together with their clinical and psychological stakeholders, to revisit the field of VR and to consider whether or not a more "generic" form of virtual environment, one unrelated to the context in which the original trauma occurred, may offer potential in future psychological and physical rehabilitation therapies. One particular domain that (at an early stage of development, at least) appears to offer great potential, particularly in the exploitation of a small number of virtual scenarios across a wide range of rehabilitation applications is that of *restorative environments*. Restorative environments are locations and scenes that, by virtue of their natural beauty and peacefulness, can significantly help to reduce the body's reactivity to stress and restore cognitive or attentional capacities to their "necessary levels for adaptive function" [16].

24.2 Restorative Environments

Stephen Kaplan [33], of the University of Michigan, wrote in 1992:

> The difference between nature as an amenity and nature as a human need is underscored by this research. People often say that they like nature; yet they often fail to recognize that they need it … Nature is not merely 'nice'. It is not just a matter of improving one's mood … rather it is a vital ingredient in healthy human functioning.

Significant global attention is being paid to the relationship between human physical and mental well-being and the availability and status of the urban and natural environments in which they find themselves. Research results suggest that exposure of individuals to these natural, or restorative settings can promote stress reduction (e.g. [31, 64]) and assist the recovery of attentional capacity and cognitive function following mental activities, or fatigue brought on by "directed attention" (e.g. [3, 4, 32, 34]).

Restorative environments as simple as window views onto garden-like scenes can also be influential in reducing post-operative recovery periods and analgesic administration. In an oft-cited paper published in *Science*, Ulrich [65] compared 23 matched pairs of patients who underwent a cholecystectomy (gall bladder surgery). After surgery, patients were randomly assigned either to rooms facing a brick wall, or rooms with a view of a natural environment (such as trees or a grassy field). Ulrich found that those facing the natural view had shorter post-operative stays, took fewer analgesics, and rated their hospital stay as more positive than those facing the more "urban" scene.

In 2004, the influence of the immediate environment on patients' sense of wellbeing and post-operative recovery was acknowledged in a report from National Health Service (NHS) Estates [36]. This particular study showed that architectural environments can contribute to the treatment of patients and have a significant impact on their health outcomes. The report concluded that patients make better progress in purpose-designed modern buildings than in older ones and that better designed hospitals create an overall improved atmosphere, leading to patients with mental health problems being less confrontational and general patients requiring less analgesic medication.

Research by Tsunetsugu and colleagues from the Japanese Forestry and Forest Products Research Institute addressed the exposure of subjects to forest and urban settings and the effect that these exposures had on subjective ratings and physiological measures, including blood pressure, heart rate and salivary cortisol excretion [46, 63]. Their research demonstrated that 15–20-min exposures to natural environments, such as a broadleaf forest (the Japanese use the term *Shinrin-yoku*, or "forest bathing"), were accompanied by significant lowering of blood pressure, pulse rate and cortisol levels when compared to similar exposures in a busy city area. Subjective ratings of "calm", "comfortable" and "refreshed" were higher in forest conditions than those recorded in the city. More recent results from these research teams have demonstrated a link between forest bathing and significant increases in the number and activity of human Natural Killer (NK) cells. An important part of the immune system, these cells play a major role in the suppression and eradication of tumours and viral infections (e.g. [38]).

Li et al. attribute this effect in part to significant reductions in measured urinary adrenaline (the "stress hormone") and also to the release by forest trees of phytoncides—active plant substances (e.g. wood essential oils) that can inhibit the growth of, even kill bacteria, fungi and microorganisms. Indeed, these effects appear to persist for up to a week after initial exposure to the forest environment. The Japanese Government takes *Shinrin-yoku* very seriously indeed and, at the time of writing, has already invested over $US4 million in research, with the aim of establishing 100 Forest Therapy sites within a decade and, thus, promoting a more non-destructive use for the forests that cover nearly 70 % of the country.

Other indicators of human response to real-world restorative environments include reductions in blood pressure [24] and cortisol [69]. Research also suggests that a reduction of symptoms related to prolonged stress and depression, including those brought about by prolonged adverse weather and annual time changes—a form of "constrained restoration"—can occur as a result of exposure to green spaces and rural outdoor settings [23]. This may even benefit those who suffer from Seasonal Affective Disorder (or "SAD"), a form of seasonal depression characterised by episodes that can re-occur at similar times each year, typically in the winter. The main symptoms of SAD include a low mood and a loss of interest in day-to-day activities, longer sleep periods and weight gain.

Why do these effects occur? Two theories have been put forward by the early proponents of restorative environments, although neither has the benefit of strong background evidence or experimental support. Kaplan [34], for instance, makes reference to *Attention Restoration Therapy* where, it is claimed, when interacting with a rural environment that is "rich with fascinating" (but subtle) stimuli, attention is "modestly" captured in a "bottom-up, involuntary fashion", allowing directed attention mechanisms to recover. Urban environments also contain "bottom-up" stimuli (e.g. flashing lights, loud "man-made" sounds, signs, etc.), but these "dramatically" capture attention and require directed attention to overcome the impact of the stimuli.

In contrast, Ulrich [64] proposes an *Affective Response Approach* in which sensory patterns within an individual's field of existence prompt automatic and quite dramatic responses. Natural patterns (e.g. from rural environments) lead to a "replenishment of cognitive capacity" by altering the emotional and physiological states of the individual—the initial affective response shapes the cognitive events that follow. Discussions and exchanges relating to the underpinning theory of restorative environments will, no doubt, continue unabated for some time. However, as pointed out by Valtchanov et al. [68], "since the emergence of these two theories, the questions of "how" and "why" restorative environments reduce cognitive fatigue, decrease stress levels, and increase an individual's ability to focus have not been thoroughly researched".

More recently, work has been conducted to investigate the role of water features in rural and urban scenarios (i.e. the presence of visible amounts of standing or running water that may dominate, or be secondary features in a scene) on mental health and well-being. Initiatives in the UK such as Green Gyms and, more recently, *Blue Gyms*, are based on the premise that exposure to, and activities within woodland and coastal habitats offers natural health-enhancing benefits [11, 12].

24.3 "Surrogate" Natural Environments

Of course, all of the above examples relate to real-world exposures, be the participants healthy or undergoing a period of hospitalisation. But what of individuals who are unable to access and experience real natural environments—patients who present with a variety of psychologically-related conditions (e.g. PTSD,

Fig. 24.2 Static images and murals in a hospital environment

depression, attention deficit disorder, pain and sleep deficit, to mention but a few) and who may be confined to sensorially sparse rooms and wards within urban hospitals, hospices and care homes, or within civilian and military rehabilitation centres? Is it possible that VR technologies could be developed to achieve similar psychological and physiological effects to those described above? And could these technologies deliver a new form of therapeutic process that could be used and reused in a variety of passive and dynamic contexts—from recovery in Intensive Care Units to minimising muscle atrophy prior to the fitment of prosthetic limbs? If so, and to pose a question asked by Wohlwill in [74], "what would it take to simulate a natural environment, one that would in fact be accepted as a satisfactory surrogate"?

24.3.1 Image- and Video-based Restorative Environments

The use of static images as restorative environments includes posters or large-format photographs, murals or wall paintings, interior decor resembling rural settings (e.g. forest, coastal or lakeside locations; see Fig. 24.2) and browsable image portfolios of high-quality natural scenes. A considerable amount of the available literature appears to focus on subjective, "preferential" studies relating to the use of images of natural settings for such applications as marketing/product branding (e.g. [37]), or judging views from hotel, apartment and hospital windows (e.g. [6, 39, 57, 72]).

With regard to healthcare issues, as opposed to simple preference assessments, Diette et al. [13] investigated the use of simple pictures ("murals") of natural scenes placed at the bedsides of patients due to undergo investigation via flexible bronchoscopy. The patients also received taped sounds of nature (such as a babbling brook) before, during and after the procedure. Patient ratings of pain control (using a 5-point scale ranging from poor to excellent) and anxiety showed that, in contrast to a control group, distraction therapy exploiting natural audio and visual stimuli significantly reduced pain but not anxiety.

Nanda et al. [40] presented a review of literature addressing art and post-traumatic stress for war veterans. The review acknowledges the literature relating to the therapeutic effects of using natural images, and lists Ulrich and Gilpin's [66] suggestions for health care art, which include waterscapes, landscapes, "positive cultural artefacts", flowers, and "figurative elements with emotionally positive faces". However, the authors highlight that this has not been explored in the context of PTSD, specifically of war veterans, and emphasise that careful consideration of veterans' PTSD symptoms is warranted before any visual imagery is selected for environments providing health care to veterans.

Video representations of restorative environments include background/at-bed/at-chair looping videos presented via projectors or plasma/flat-screen displays (also hospital entertainment screens), as well as closed-circuit television (CCTV) images relayed to the observer from remote external environments. Ulrich et al. [67]—conducted an experiment using over 870 blood donor participants (68 % males and 32 % females with a mean age of just over 40 years), exposing them to four different environmental conditions, presented using a video player and wall-mounted screen. The conditions were (1) footage of natural environments, (2) footage of urban environments, (3) daytime television and (4) a blank screen. Using physiological measures (blood pressure and heart rate), the researchers found that stress was lower during the blank screen condition than the daytime television condition, and lower during the natural environments condition than the urban environments condition. Throughout, pulse rates were markedly lower during the natural environments condition than the urban.

Friedman et al. [17] describe two individual participant case studies in which a high-definition television (HDTV) installed in the participants' windowless offices relayed a view from an external camera overlooking a public plaza and fountain area in real-time. The results of the studies exposed contrasting opinions. On the one hand, participants found the display psychologically and socially beneficial in terms of an increased sense of "connection", offering mental breaks.

In a later paper, Friedman et al. [18] reported an increase in users' connection to the wider social community, connection to the natural world, psychological wellbeing, and cognitive functioning. However, in both publications, a number of negative issues were identified as well, including the potential for the camera system to be distracting and leaving participants with "an immoral sense of surveillance", specifically concern about the privacy of people whose images were being captured in a public place. Kahn et al. [30] further reported that participants took "mental breaks" to stare at the external views, returning more refreshed. Participants also felt connected to the days passing due to movement of the sun and weather changes.

Abkar et al. [1] performed an experiment in which stress was induced in participants by showing them a video of an accident with excessive blood and gore. To recover from this stress, participants were either shown a video of natural scenes (e.g. trees, moving water, grass) or traffic. Building on the earlier findings of Ulrich et al. ([67], *op cit.*) and van den Berg [69], who also demonstrated a range of positive effects of films of real nature, Abkar et al. found higher levels of stress recovery in the participants who viewed the natural scenes, as determined by blood pressure, muscle tension and heart rate. The study showed that the natural setting could elicit responses which included an element of the parasympathetic nervous system linked with the restoration of physical energy.

24.3.2 Virtual Reality-Based Restorative Environments

VR restorative environments use similar at-bed/chair/wheelchair presentational techniques as the video presentations described above, but, if implemented appropriately, will support a greater degree of interaction on the part of the user (e.g. virtual environment navigation and exploration; virtual object interrogation; interaction with virtual actors, or avatars etc.) and a more cost-effective means of updating the scenery on a regular basis. One of the surprising discoveries whilst conducting the literature search in support of this report was the significant absence of relevant research and experimentation in the field of virtual restorative environments (VREs; i.e. those built using established VR or "serious games" toolkits) for post-operative recovery and their subsequent extension to support rehabilitative procedures. This finding is confirmed in the writings of de Kort and Ijsselstiejn [10], who point out that the majority of studies have involved the use photographs, slides or videos in a laboratory setting. Unfortunately, they go on to report the results of three studies that are, themselves, based on passively-presented video material of natural environments, where participant "immersion" was defined on the basis of screen size. Of the few studies discovered, only a tiny proportion report relevant experimental findings, most focusing on "what if" issues or the outcome of subjective analyses, many concluding that virtual natural environments "may" have "some degree" of restorative qualities. However, two studies are worthy of mention here.

The first, reported by Waterworth and Waterworth [71], was based on what the authors described as a virtual "tropical paradise", developed as part of a European Union (EU) project called EMMA (Engaging Media for Mental Health Applications). It seems that the EU grant expired before the research team could actually perform any meaningful experiments with their particular VE (despite a funding period of some 8 years), although they [50] claim to have developed a "bio-cultural theory of presence". The EMMA *Paradiso* VRE, referred to as "Relaxation Island", is described by Waterworth and Waterworth (*op cit*.) as "an archetypical tropical paradise, with lush vegetation, a waterfall and a long beach, all surrounded by mountains …". Unfortunately, this tends to raise the expectation of the reader, who is then confronted with images of a relatively low-fidelity VE, together with images of an interactive control device resembling a pearl in a sea-shell. The aim of this VRE is to achieve "equal or even greater levels of relaxation without relying on imaginative skill" (as might be achieved during early stages of hypnosis, for example). Whilst on the island the participant can choose any of four zones to learn different relaxation techniques. Two of the zones are beach locations, the third is a waterfall and the fourth a "cloud zone". A "calm voice" instructs each participant in the different relaxation exercises at each zone. At the waterfall zone, for example, the therapist is able to enter "worry words" elicited from the participant, each of which appear on the leaves of a nearby plant, before falling into the stream to be carried out to sea.

The second study, by Valtchanov et al. [68] provides early findings supporting the use of VREs and their similarity in delivering enhanced feelings of well-being as might be achieved using, for example photographic images or videos ("surrogate nature"). A photorealistic forest covering some 1,600 m^2 was constructed and presented to participants wearing a head-tracked HMD. In addition to the HMD, a "rumble platform" was also used, providing haptic cues to represent taking steps and colliding with objects within the VE. Navigation through the VE was achieved using the buttons of a wireless mouse—moving the participant's viewpoint forward and backward along the current axis of view. Heart rate and skin conductance sensors were mounted onto the participant's non-dominant hand and pre-VE exposure stress levels were induced using a variety of techniques, including self-described stressful experiences accompanied by loud urban noise, followed by the Markus–Peters Arithmetic Test [48]. Participants were then exposed to the virtual forest environment, allowing them to explore the environment freely for ten minutes (participants in the control condition were exposed to a slideshow comprising ten abstract organic paintings). Skin conductance was found to decrease significantly following exposure to the VRE, although there was no significance in heart inter-beat intervals between the experimental conditions.

24.4 The Virtual Restorative Environment Therapy Project

VRET is a project that originated from postgraduate research conducted at the University of Birmingham in the UK (and is still in progress at the time of writing). The long-term aim of *VRET* is to develop a range of VREs for the benefit of patients who present with a variety of psychologically-related conditions (e.g. PTSD, depression, attention deficit disorder, pain and sleep deficit) and who may be unable to access and experience real natural environments, including those in hospitals, hospices, civilian and military rehabilitation centres and care homes [12].

Fig. 24.3 Scenes from *Virtual Wembury* (*left*) and *Virtual Burrator* (*right*)

Another aspiration for the *VRET* project is to conduct fundamental Human Factors research, using the VEs developed as a test bed, into a range of interactive technologies and software packages and psychophysiological measures of human performance, immersion and well-being. At the present time, *VRET* is based around two virtual environments, both representations of real-world locations in the south of Devon–Burrator Reservoir and Wembury Bay.

In brief (and with additional material and images available at www.virtual.burrator.net and www.virtual-wembury.net), both environments (Fig. 24.3) were developed using a variety of 3D modelling, image processing and run-time tools.

The virtual topography of the environments were based on commercially available Digital Terrain Model (DTM) data—dense fields of digital elevation points at a resolution of 5 m and a vertical accuracy of 1 m. Once the DTM models were converted into a polygon-based mesh, the virtual terrains were of a form suitable for importing into the *Unity3D* toolkit, where they were flat-shaded and endowed with a high-resolution texture map, itself generated from an aerial photograph of 12.5 cm ground-equivalent resolution. This texture map provided the development team with a visual template which was invaluable in helping to locate key natural and man-made features—trees, large plants, meadows, rocks, streams, buildings, paths and enclosures. The virtual counterparts of these and many other features were either sourced from the Web, or "built" from scratch using the *3ds Max* or *SketchUp Pro* modelling tools. A series of photographic, video and sound surveys were also conducted. Sounds of birdsong, water, wind and footsteps were then programmed into the VE, to create a dynamic soundscape which varies depending on the end user's spatial location. Real time of day (24-h day–night cycle) and simple weather effects were implemented, using the *UniSky* software system, and particle-based mist and spray effects were also included where it was felt they added a desirable visual quality.

The VREs can be displayed to the end user using a range of devices, from HMDs to plasma screens and projectors. Exploration of, and interaction with the VE can also be implemented using a range of devices, from basic keyboard and mouse to multi-function hand controllers, such as the *Xbox* gamepad (Fig. 24.4, left-hand images), the low-cost *Zeemote JS1* (used for mobile gaming) and Razer *Hydra* systems (Fig. 24.4, lower right-hand images), and the Asus *Xtion* motion

Fig. 24.4 Selection of images showing the interactive display and control elements of the *VRET* experimental modules (specific descriptions given in the main text)

tracking device (as mounted above the displays shown in Fig. 24.4, left-hand images). The ability to tailor the human-system interface to support appropriate styles of interaction based upon the specific physical conditions presented by the patients (military casualties including amputees, burns victims, etc.) is absolutely essential, if their early and positive engagement (and that of the nursing personnel) is to be successful.

24.4.1 Early VRE Pilot Studies

Evaluating the impact of the two *VRET* environments on the recovery of hospitalised patients and on the health and well-being of other potential groups of beneficiaries will, of necessity, demand a long-term period of research and experimentation. Although early, informal presentations of *Virtual Wembury* and *Virtual Burrator* to clinical specialists and other healthcare workers have been met with considerable support, the process of introducing the technology into hospitals is a slow and painstaking process. Ethical applications supporting the involvement of both civilian and military patients in experiments using the *VRET* technology can take many weeks, even months. Furthermore, as the technologies invariably need to be changed or modified between experimental sessions as a result of user feedback and observational findings, new applications have to be submitted. Consequently, the execution of simple pilot studies in parallel with

Fig. 24.5 Plan view (*left image*) and first-person view (*right image*) of a simple virtual town environment

these applications, using healthy participants, is an essential part of the *VRET* programme. Such studies help the research team to identify and prepare for any usability issues that may become evident prior to hospital deployment. A small selection of such pilot studies are presented below.

To support the evaluation of interactive technologies, two mobile display modules have been developed (Fig. 24.4, lower middle image). Each module consists of a 50-inch plasma display, an appropriately graphics-enhanced computer or laptop and a selection of interactive controllers (some of which are described below) all mounted onto a multi-shelf trolley. Close attention has been paid to the safety and hygiene aspects of design, with all exposed elements made accessible for cleaning and all wires enclosed within plastic sheathing.

24.4.1.1 Pilot Study 1: Context-Appropriate Sound Effects

The first pilot study experiment focused on a comparison of natural (*Virtual Wembury*) and urban virtual environments, with an additional aim of assessing the effect of adding realistic ambient, or "context-appropriate", sound effects. Fourteen undergraduate student participants took part in the study (12 males and two females with a mean age of 20 years). The participants' task simply involved a "free-play" style of navigation around the VEs (using a *Zeemote JS-1* controller), both of which were presented using 50-inch plasma screen. Both the city and coastal scenes were completed under two conditions, with sound and without sound. In the conditions with sound, this was presented to the participant through headphones. In the town scene (Fig. 24.5), the sounds presented included footsteps of the virtual participant and traffic (simple moving vehicle models were a feature of this environment). In the coastal scene, the sound of footsteps was also included, together with natural sounds, such as the waves of the sea, wind and birds. In the conditions without sound, the participants wore the headphones but no sound was presented.

Subjective responses of anxiety and relaxation were recorded on a 10-point rating scale. In summary, mean ratings of anxiety were slightly higher in the town context than the coastal context, although the differences were not statistically significant. Relaxation was rated slightly higher in the coastal environment than in the town, although again not to any level of statistical significance. In the town environment with sound, anxiety increased and relaxation decreased; in the coastal scene, anxiety decreased and relaxation increased.

24.4.1.2 Pilot Study 2: Detection of Synthetic Smells

The second pilot study experiment was highly exploratory in nature and was conducted to determine whether or not the introduction of a synthetically-generated smell into a VRE would cause a physiological response that could be detected objectively and unobtrusively. Note that the aim of this investigation was *not* to evaluate any therapeutic value or immersive effect that might accompany an olfactory stimulus. Rather, the study was conducted simply to assess whether or not the available technology (a *ScentScape* 20-smell display system from the US company Scent Sciences) produced an olfactory stimulus that could be detected and would, therefore, influence basic psychophysiological measures. The experiment also provided an opportunity to gain experience with recording electro-dermal activity (EDA; also known as galvanic skin response, or GSR) whilst interacting with a VRE, with the aim of assessing the technology's sensitivity in detecting affect-related physiological parameters and participant stress levels.

The experiment employed the *Virtual Wembury* coastal environment as described above, with ambient sounds delivered by headphones for all conditions. Within the coastal environment, the participants (14 undergraduate male students of similar mean age to those in the first experiment) were directed simply to "walk" from one end of the coastal path to the other. This took approximately 3 min, although the participants were aware that they were not under any time pressure to complete the task. The participants walked the virtual coastal paths under two different smell conditions and a third condition with no smell, used as a control. The delivery of the smell was triggered using a *Wizard-of-Oz* protocol, whereby the experimenter initiated the smell signal after approximately 90 s of virtual walking. The exact time that the smell was triggered was recorded so that it could be synchronised with the physiological recordings.

The choice of scents used in the experiment was limited by their availability, as was the number of times that each one could be used. Seven different scents were used. These were: Damp Forest, Balsam Fir, Floral, Jasmine, Lavender, Lilac and Burning Electrical. Six of the scents represented natural aromas, two woodland (Damp Forest and Balsam Fir) and four floral (Floral, Jasmine, Lavender, Lilac). Burning Electrical was used to represent a smell that would be somewhat incongruous with the environment and, as it signified burning, might possibly trigger a warning response.

Pulse rate was recorded using a finger pulse oximeter worn on the distal end of the index finger. EDA was recorded using a ThoughtStream Biofeedback USB System with electrodes strapped across the surface of the interdigital palmar pads. Both the pulse oximeter and EDA electrodes were attached to the left hand, which was placed on a table such that the forearm was supported horizontally at waist height. Locating both sensors on the left hand also enabled the participants to use the *Zeemote JS-1* controller with their right hand. Pulse rate and EDA data were recorded to a PC continuously throughout all conditions for subsequent offline analysis.

Approximately two-thirds of conditions involving the presentation of smells produced skin conductance responses (SCRs) that were visually discernible, with a >0.5 μS increase in conductance following the onset of the olfactory stimulus. Between the different smell stimuli, "Burning Electrical" produced the greatest ratio of discernible SCRs (5:1). The smells representing natural odours (woodlands and flowers) produced an overall discernibility ratio of approximately 2:1. For all conditions where a smell was presented, it was detected by all participants. There was also a relationship between the subjective rating of pleasantness of the smell and the incidence of SCRs, with smells rated as unpleasant being more likely to produce SCRs than smells rated as being pleasant. The majority of the smell conditions produced intensity ratings at "Strong" or higher on an Odour Intensity Scale. The results of the pulse data showed no indications of change in heart rate following the presentation of a smell.

The use of an olfactory display as part of an interactive VRE system is considered by the authors to be worthy of further in-depth investigation, although it is clear that that the technology is still at a very immature level of development. One issue of concern is the inability of current COTS technologies to achieve sustained and silent delivery of aromas, not to mention their rapid removal and replacement as end users enter different zones within the VRE (e.g. transiting from the water's edge in Virtual Wembury to more inland locations, such as the coastal path and woodland area). The issue of silent delivery was less of a problem with the *ScentScape* system than, for example, the *ScentPalette* product (marketed by Virtually Better Inc.), where the onset of the system's compressor and pneumatic delivery components were found in earlier informal evaluations to generate significant noise levels, effectively alerting the end user to the onset of an aroma before that aroma was even released. Another issue worthy of exploration relates to cultural differences in aroma perception. In the experiment described above and in presenting the technology to students undertaking courses in Interactive 3D Technologies, it has become apparent that there are significant cultural differences in how aromas are perceived. For example, scents obtained from US sources labelled as "hospital", "newly mown lawn", "fresh breeze" and "mid-east spice", to mention but a few, elicit different olfactory interpretations from students from the UK and Far East.

Of course, in the UK at least, and for the foreseeable future, the use of fan-delivered olfactory displays in many hospital locations will be prohibited due to hygiene issues and the potential for transmitting airborne diseases. Nevertheless, the use of aromas and, indeed, the potential effects on human well-being of inhaling phytoncides (e.g. Li et al., *op cit.*) contained, for example, within aromatherapy essential oils, is definitely worthy of further academic investigation.

24.4.1.3 Pilot Study 3: Initial Hospital Usability Trials

In conjunction with medical and nursing staff at the Queen Elizabeth Hospital, Birmingham (QEHB) and the Royal Centre for Defence Medicine (RCDM), a series of usability pilot studies have been conducted within the hospital's main Military Ward and Intensive Care Unit (ICU). The aim of these studies was to observe the patients' interactions with the *VRET* environments using a variety of display and control devices.

In the case of the military patient trials, interaction—simple forward and backwards motion through the *Virtual Wembury* scenario, together with look right/left motions—was provided via the thumbstick component of the *Zeemote JS1* hand controller mentioned earlier. In order to take an early opportunity to gauge the participants' reactions to typical VR technologies, the virtual environment was presented using a Vuzix *Wrap* 1200VR HMD and Sony audio headphones (although the 6-degree-of-freedom head tracker made available with the Vuzix HMD was not activated for this investigation). To capture the patients' early comments relating to the usability of the *VRET* technologies, a subset of the items featured in the System Usability (Likert) Scale (SUS), a popular and "technology agnostic" tool [2] developed by Brooke [7], was used after each trial with the *VRET* system.

In general, the military patients found the technology highly usable and easy to master, and their general comments about the future use of VEs for helping patients to recover were very positive. Despite this, however, there were a number of occasions where it became obvious that the interactive technologies were causing a significant degree of frustration. In particular, the *Zeemote* hand controller was not appropriate for at least one of the participants who, as well as being a lower limb amputee, had experienced significant damage to both hands and forearms. His ability to grip the controller was, therefore, compromised and it was obvious that a larger handgrip (such as the Razer *Hydra*, mentioned earlier) would have been more appropriate. Adjusting the Vuzix HMD was also difficult for this patient, although similar observations were made for three out of the five participants. This confirms the earlier statement that, for future exploitation of these VREs, it will be important to assess each user to ensure that the interface technologies provided do not constitute a barrier to the individual's ability to interact with the virtual worlds.

Turning finally to the introduction of the *VRET* system into the QEHB Intensive Care Unit, this took the form of a short single-participant observational study. The elderly female participant, from whom consent for the investigation was obtained in advance, agreed to be exposed to a complete interactive display unit as shown in Fig. 24.4 (top right-hand image) and additional permission was obtained from the patient's relatives, who were in attendance throughout. For this investigation, taking into consideration the patient's general condition, limited arm and hand functions and, consequently, the potential for rapid onset of fatigue, it was decided to investigate the use of a simple "retro" (2-axis) style of gaming joystick, such as those originally made available for Atari and Commodore video consoles.

The observational results were very interesting indeed and covered a multitude of patient- and environment-centric issues. From an environmental perspective, it

Fig. 24.6 The genius ring mouse control device

was found that the location of the display unit was crucial to the patient's ability to appreciate the colours and forms of the *Virtual Wembury* environment. Screen glare caused by nearby windows (even those with blinds) was unacceptable, and the visual quality of the displayed images was made considerably worse by the use of smearing caused by the use standard hospital antiseptic wipes. In addition to this, it was discovered that the screen size (50 inches) was felt by the patient to be too big and in some instances was causing some disorientation. At the time of writing, new trials are under way using a 32-inch screen mounted on an extendable bracket, which enables the screen location to be adjusted to the patient's preference. The feelings of disorientation were exacerbated when the patient's relatives requested to try the system (an unsurprising effect when on-screen motion is outside of the control of the end user and one that should be discouraged in future deployments).

The "retro" joystick was also found to be inappropriate for this particular patient—the fatigue evident in her upper limb made fine control of the on-screen activity almost impossible. Following this finding, an alternative method of interaction has been implemented which exploits another COTS product, the Genius *Ring Mouse* (Fig. 24.6), a Wireless device which possesses a sensitive thumb cursor controller. In cases where the end user is unable to navigate freely throughout the virtual environment, he or she can use the *Ring Mouse* pushbuttons to "toggle" between pre-selected views and, once arriving at the view of choice, can look around by gently stroking the sensitive thumb pad.

24.5 Conclusions

The application of VR to therapeutic support in psychological treatment régimes has been demonstrated to good effect since early so-called "immersive" technologies were effectively applied during systematic desensitisation treatments of certain phobias in the 1990s. However, more recent exploitations of VR—in such fields as PTSD, for example—have met with varied levels of success. This is due, in part, to a preoccupation with delivery technologies (HMDs, haptic and proprioceptive simulation, CAVEs, olfactory displays and the like) and attempts to recreate accurately the details of events leading up to, and triggering an individual's response to a traumatic event. Early research efforts conducted by the author's team in conjunction with clinical psychologist stakeholders and pain management specialists led to the conclusion that such an approach to exploiting VEs is unlikely to be successful, except in one or two chance instances. To develop a VR system worthy of exploitation in a clinical setting, such that within a week or two of referral, the specific environmental and psychological events leading up to a personal traumatic experience could be simulated to an appropriate level of fidelity is, given today's technological capabilities, almost impossible. Indeed, this situation is likely to persist for many years to come and, even then, such a capability would demand the design and programming talents equivalent to that of a large, established entertainment games company.

Nevertheless, the use of VR and games-based technologies in psychological therapies for defence-based medical contexts, not to mention the support of more generic healthcare applications, is worthy of continued investigation, especially in enhancing patients' recovery profiles following surgical procedures, from intensive care to the hospital ward. VR also offers potentially significant benefits to patients in subsequent general health, well-being and rehabilitation programmes. This is especially the case for amputees who, whilst awaiting the fitting of prosthetic limbs, could benefit from interactive technologies providing a strong motivational means of delivering pre-prosthetic exercises, thereby avoiding muscle atrophy and related reductions in residual capabilities. In contrast to the use of static images and "canned" videos and even CCTV images relayed to the patient's bedside from external sources, VREs possess a range of important qualities, not least significant of which is *real-time* interaction and ease-of-editing, supporting the generation of scenarios that can be tailored relatively easily to meet the needs of individual patients.

The experience of introducing the *VRET* simulations into the Military Ward and ICU at QEHB has been very positive indeed. Patients' suggestions for future development, especially with regard to interactive tasks and "games", were many and varied and included hang-gliding, scuba-diving, treasure hunts and a selection of multi-user, competitive sports. Whilst many of the suggestions will require considerable effort to implement (even with today's highly usable and flexible VR/serious games toolkits) there is no doubt that, beyond the provision of basic restorative virtual environments, the main research and development challenge will be providing unobtrusive and intuitive interfaces to enable patients with traumatic injuries, especially amputees, to indulge in more dynamic activities. A further challenge will be to work closely with the nursing and physiotherapy specialists at QEHB to tailor these dynamic activities such that, rather than providing the amputees with basic games environments, they actually encourage the development of movements in residual limbs and stumps that help prevent muscle atrophy and, effectively, prepare the patients for the later fitting of their bespoke prosthetic devices. As pointed out by Rego et al. [49], "existing (serious) games could be modified in order to … become more functional tools for … rehabilitation therapy". They go on, "… rehabilitation games have not yet fully explored most of the entertainment characteristics games can provide. Thus, a direction for future work is to identify and measure the impact of the more relevant aspects that can improve the suitability and effectiveness of a game for rehabilitation". They conclude, "How to attain collaboration or competition, when patients are at different stages of the rehabilitation process or have different handicaps is an important research problem".

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Chapter 25
Virtual Reality Graded Exposure Therapy as Treatment for Pain-Related Fear and Disability in Chronic Pain

Thomas D. Parsons and Zina Trost

Abstract Pain-related fear and concomitant avoidance behavior have been identified as major contributors to development and maintenance of chronic musculoskeletal pain and disability. While graded exposure therapy (GEXP) is advocated as one of the most effective strategies for reducing pain-related fear and disability, its practical utility and large-scale dissemination have been limited. The current chapter describes a novel virtual reality (VR) methodology to optimize exposure-based treatment for individuals with chronic pain, focusing specifically on chronic low back pain (CLBP). Virtual Reality Graded Exposure Therapy (VRGET) promises to address several major limitations characterizing traditional GEXP approaches and to incorporate cutting-edge disability-relevant assessment and intervention. Specifically, VRGET is able to mitigate costs traditionally associated with GEXP treatment, enhance participant engagement with treatment, provide real-time assessment of important metrics such as affective response and kinematic adaptation, and promote generalizability of rehabilitation gains across clinic and home environments.

25.1 Background and Introduction

Musculoskeletal pain is the dominant type of chronic pain affecting the world population, exerting an enormous impact on individuals, societies, and health care systems [18, 150]. Musculoskeletal pain conditions are the leading cause of disability in the United States and represent more than half of all chronic conditions among individuals over 50 in developed countries [33]. Among musculoskeletal pain conditions, back pain is the most common. In particular, the

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incidence of low back pain has reached epidemic proportions, affecting up to 84 % of adults at least once in their lives [26]. Most acute low back pain episodes are self-limited, with symptoms remitting within a few weeks and calling for little or no intervention. However, it is estimated that up to 10 % of low back pain sufferers develop a chronic pain condition characterized by long-term pain and associated disability [99]. This minority of the population accrues great health-care and societal costs, consuming more than 50 % of all resources allocated toward back pain [7, 85]. In addition to economic burden, physical limitations stemming from back pain often interfere with activities central to one's identity (e.g., as a parent, spouse, friend, worker), thus fostering role loss and identity erosion [32, 52, 126].

Despite increasing sophistication of medical interventions, the burden of back pain continues to rise [33], suggesting a need for novel intervention paradigms to complement traditional treatment options. Virtual reality (VR) technology provides a new and promising approach for pain and disability management by capitalizing on advances in current understanding of the biopsychosocial etiology and maintenance of back pain problems.

The organization of this chapter is as follows. Section 25.2 will present a brief overview of the Fear-Avoidance (FA) model of low back pain [142], which has emerged as a leading biopsychosocial formulation of disability development and maintenance following acute back injury. Section 25.3 will describe the intervention approach informed by this model, namely Graded Exposure in vivo (GEXP) as well as its current status and limitations. In Sect. 25.4, there will be a general discussion of virtual reality and its use in non-pain specific exposure therapies and pain distraction. Section 25.5 will explore areas in which a virtual reality graded exposure therapy (VRGET) may enhance current approaches. The conclusion briefly summarizes the main ideas of this chapter.

25.2 The Role of Pain-Related Fear in Disability

The FA model offers a cognitive-behavioral account of why some individuals with an acute musculoskeletal injury go on to develop chronic pain and disability, while others do not [65, 142]. According to the model, fear that movement or physical activity will exacerbate pain or prompt (re)injury—also known as pain-related fear—is underscored by catastrophic appraisals of pain sensations [48, 123] that promote a self-perpetuating cycle of behavioral avoidance, hypervigilance, depression, and disuse, resulting in functional disability (see Fig. 25.1).

Pain-related fear has emerged as a robust predictor of pain and disability at acute [42, 48, 101, 102, 123, 128], and chronic [19, 47, 80, 143] stages of back pain. Critically, individuals high in pain-related fear endorse beliefs that pain is a sign of serious tissue damage, as well as high motivation to avoid exertion or activity that might contribute to pain and therefore to perceived physical damage [42, 101, 128].

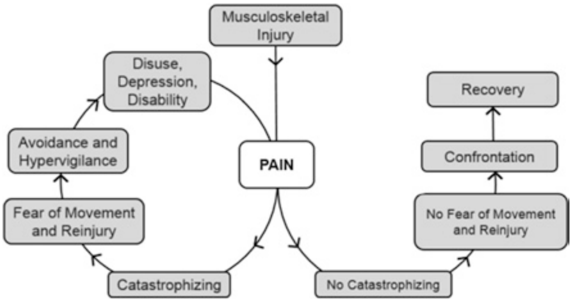

Fig. 25.1 The fear-avoidance model of low back pain

Because return to regular physical activity is crucial for successful recovery from acute injury, avoidance is conceptualized as a key mediating variable in the progression from acute to chronic pain sensations [48, 123]. Consistent with predictions drawn from the FA model, research with individuals suffering from chronic low back pain (CLBP) reliably links pain-related fear with escape from and avoidance of physical activity, resulting in impaired behavioral performance [143]. Among individuals with higher pain-related fear, avoidance is reflected in both limited physical exertion and behavioral strategies (e.g., guarded movement patterns) adopted to ostensibly reduce pain/harm [19, 80]. While some avoidance of physically stressful activity is a natural response to protect damaged tissues following injury, prolonged avoidance of physical activity is known to detrimentally affect various physical/physiological systems [101, 102], which through multiple mechanisms can serve to maintain disability and actually increase the chance of further injury [19, 80]. Furthermore, since avoidance behavior occurs in anticipation of, rather than in response to pain, opportunities to receive corrective feedback regarding erroneous catastrophic pain beliefs are limited [65].

It is important to note that although the current chapter focuses on chronic low back pain as a model for examining the proposed VRGET intervention, pain-related fear has been shown to predict pain, disability, and rehabilitation outcomes across a number of traumatic, chronic, and progressive musculoskeletal disorders. These include conditions such as spinal cord injury [136], fibromyalgia [75], and osteoarthritis [54, 125] as well as outcomes following medical and surgical interventions such as total knee replacement [127]. The treatment approach described below (GEXP) has likewise been successfully applied across a range of disabling pain conditions [141].

25.3 Treating Pain-Related Fear and Avoidance Behavior: Graded Exposure In Vivo

How do high fear CLBP patients recover from avoidance behavior? Evidence suggests that a type of cognitive-behavioral therapy—specifically, graded exposure in vivo (GEXP)—is among the most effective means of reducing pain-related fear,

Fear Hierarchy

Harm Rating	**Physical Activity (*Rating*)**
Extremely harmful to the back **100**	
	1. Pick up a child *(99)*
	2. Load groceries into car from shopping cart *(95)*
	3. Carry laundry *(80)*
	4. Vacuum for extended period *(75)*
	5. Perform twisting motion with trunk *(60)*
50	6. Go up and down the stairs *(50)*
	7. Bend forward (e.g., tie shoes) *(45)*
	8. Reach up (e.g., put away dishes) *(43)*
	9. Rake the leaves *(25)*
	10. Raise arms above head *(20)*
	11. Make bed *(25)*
Not harmful at all to the back **0**	

Fig. 25.2 Typical hierarchy of feared and avoided activities. Activities higher on the scale are those thought to be more harmful

catastrophizing, and disability [47, 75, 136, 143]. Exposure protocols are typically delivered in outpatient or inpatient settings and involve establishment of a hierarchy of avoided activities and gradual confrontation of these feared activities through "behavioral experiments" intended to correct erroneous pain beliefs [47]. These fear hierarchies are idiosyncratic to each individual and are associated with individuals' beliefs regarding the harm/injury potential of various physical activities. An excerpt from a typical fear hierarchy is presented in Fig. 25.2. Thus a highly fearful individual may assert that picking up a child may "snap the back" or cause serious and irreparable damage.

The patient works with a dedicated clinician and often a comprehensive rehabilitation team [141]. By successive gradual exposure to previously avoided activities, individuals are able to correct catastrophic misinterpretations of pain sensations and specific harm expectancies, leading to decreased fear levels and functional improvements [47, 54, 125, 127, 136]. An increasing number of clinical studies and randomized clinical trials demonstrate the utility of exposure in reducing pain-related fear, catastrophizing, and disability in fearful CLBP adults [8, 21, 29, 66, 67, 144, 145, 149]. Outside the clinical setting, a related line of experimental research supports the effects of GEXP, demonstrating that having CLBP patients confront a stressing physical activity leads to a swift correction of overprediction regarding the pain and harm associated with that specific physical activity [20, 44–46, 133].

Despite considerable promise, existing GEXP protocols are characterized by a Woods and Asmundson [149] number of limitations. First, as delivered in the clinical setting, GEXP protocols are expensive and time consuming, relying on trained interventionists over an indefinite number of sessions [141]. Another challenge acknowledged by GEXP developers is that of patient engagement; while empirically most effective, GEXP does not appear to be a preferred manner of treatment by patients and is characterized by a high drop-out rate [41, 141]. Patient non-adherence is likely due to the anxiety-provoking nature of an intervention designed to challenge fearful pain beliefs [49].

Finally, current GEXP protocols offer only marginal metrics for understanding and tracking important aspects of rehabilitative challenges and gains. For example, although cognitive and emotional reappraisal of physical activity is conceptualized as a central mechanism of change in the treatment process, existing GEXP protocols are not able to systematically track patient affective response (i.e., fear or anxiety) to progressive physical challenge [141]. In addition, patients with high levels of pain-related fear demonstrate subtle behavioral adjustments (such as guarded movement patterns) that may function as safety behaviors, thus limiting their exposure to the feared stimulus (for example, the maximal execution of a physical activity). As will be discussed below, subtle postural adjustments during behavioral performance may actually be physically detrimental to the pain condition [129]. Current GEXP protocols offer no means to assess or intervene on these more subtle forms of avoidance. Finally, GEXP is challenged by the generalizability of treatment gains from the treatment clinic to the home environment, as well across discrete physical activities [20, 44, 46, 132]. Together, these limitations provide a compelling motivation to (1) enhance metrics for scaffolding, tracking, and establishing reliable therapeutic change; and (2) incorporate home-based access to low-cost treatment approaches incorporating GEXP.

25.4 Virtual Reality as an Instrument of Treatment

Over the past several years, virtual reality (VR) has become incorporated into a number of interventions targeting physical and psychological conditions. For instance, virtual reality applications that focus on assessment and treatment of neurocognitive [96] and affective disorders [62], as well as assessment of their component processes (i.e., attention [95], visuospatial abilities [94], navigation [2], memory [91, 92] and executive functions [97, 98]) are currently being developed and tested [88].

It is important to note that the term "virtual reality" does not limit the researcher to a particular configuration of hardware and software. Instead, VR may be understood as a development of simulations that make use of various combinations of interaction devices and sensory display systems. Typically, the design of these systems is developed with consideration of balancing level of immersiveness with level of invasiveness. Many historical users of VR have opted for highly immersive experiences using more invasive head-mounted displays (HMDs). The invasiveness results from the user wearing an apparatus (i.e., an HMD) on her or his head, which often tethers the user to a computer.

Given the desire for users to have a less invasive experience while exposed to a virtual environment, some researchers have turned to projection systems that use cameras for whole-body tracking and integration of body-state information into various simulations. These systems are noninvasive because the user is not encumbered by the need to wear accessories to enable the tracking of the user's movements. The increased availability of commercially available interaction devices (e.g., Microsoft Kinect, Nintendo Wii Sony Eyetoy Konami Dance Dance Revolution) has allowed for less invasive VR applications that present three-dimensional (3D) graphic environments on flatscreen monitors. Whilst such noninvasive VR systems involve a lower level of immersion, the phenomenoligical experience of the user is one that involves a high potential for interaction with digital content using naturalistic body actions.

VR technologies have lent themselves particularly well to exposure treatment protocols (as in the case of specific phobias) and, more recently, to the management of acute pain. As will be discussed below, the established utility of VR in these two domains provides a foundation for utilizing VR in treatments of persistent musculoskeletal pain that rely on exposure methodology.

25.4.1 Virtual Reality Exposure Therapy for Specific Phobias

Virtual reality has emerged as a novel tool for conducting exposure therapy with persons experiencing specific phobias. As part of virtual reality exposure therapy, users are exposed to computer-generated simulations or virtual environments that update in a natural way to the user's head and body motion. When users interact in a virtual environment, they can be systematically exposed to specific stimuli within a contextually relevant setting [97]. Virtual reality exposure comports well with the emotion-processing model, which holds that the fear network must be activated through confrontation with threatening stimuli and that new, incompatible information must be added into the emotional network [39, 148]. Anxiety and fear are concentrated emotional experiences that serve critical functions in organizing necessary survival responses [38]. In properly functioning affective systems, the responses are adaptive. Excessive fear responses, however, can be restrictive and may be a sign of dysregulated anxiety. When exposure to stress occurs early in development and is repeated in persons with a particular genetic disposition, a decreased threshold for developing anxiety may result [53]. Further, over-excitation and deprivation can influence the affective system and may induce changes in the emotional circuitry of the brain that can contribute to stress-related psychopathology [28].

A good deal of research has shown that exposure therapy is effective for reducing negative affective symptoms associated with specific psychopathology [110]. Moreover, in vivo exposure therapy has been found to have greater efficacy when compared to imaginal exposure, especially in the treatment of specific phobias (e.g., acrophobia, fear of driving, claustrophobia, aviophobia, and arachnophobia). Exposure to emotional situations and prolonged rehearsal result in the regular activation of cerebral metabolism in brain areas associated with inhibition of maladaptive associative processes [116]. Identical neural circuits have been found to be involved in emotion regulation across affective disorders [30, 82]. Systematic and controlled therapeutic exposure to phobic stimuli may enhance emotional regulation through adjustments of inhibitory processes on the amygdala by the medial prefrontal cortex during exposure and structural changes in the hippocampus after successful therapy [51].

The unique ability of virtual environments to match exposure to the needs of various clinical application areas has been recognized by a number of researchers interested in exposure interventions [9, 106]. Recent quantitative reviews [87, 91, 105] of virtual reality exposure therapy have concluded that virtual reality exposure has good potential as a treatment approach for anxiety and several specific phobias.

25.4.2 Virtual Reality for Pain Distraction

A recent use of immersive virtual reality has been its application to pain distraction during acutely painful experiences/interventions (e.g., wound dressing, dental pain [60]. Hoffman et al. [57, 58] contend that VR offers an effective distraction because it immerses the person using an HMD. While wearing the HMD, virtual reality-based tasks are simulated that draw heavily upon conscious attention. These VR-based tasks are understood as distractors that reduce cognitive resources available for perception of and cognitive elaboration on nociceptive input. In turn, decreased attention available for conscious pain processing has been shown to result in patients subjectively reporting less pain (see McCaul and Malott [76]). Developers of HMD-mediated interventions suggest that HMD-delivered immersive VR can offer a level of distraction that goes beyond that found in simple forms of distraction (e.g., watching videos or playing video games; see Hoffman et al. [56]). It is further argued that VR may improve analgesia through the reduction of visual cues associated with a painful procedure [57, 58]. In a recent systematic review of virtual environments designed for pain distraction, results suggest that the use of VR in adjunct with standard pharmacologic analgesics produces lower pain scores (during changes in wound dressing and physical therapy) than standard pharmacologic analgesics alone [73].

In the context of FA theory and chronic pain, there are, however, a number of problems with interventions that rely exclusively on distraction. First, although hypervigilance to pain sensations is an aspect of disability development/maintenance [137, 138], experimental pain studies suggest that individuals characterized by high fear and catastrophizing may not benefit from distraction to the same extent as their low-fear counterparts [14, 109]. Moreover, while people with high fear are particularly vulnerable for development of persistent pain, studies utilizing VR as distraction have to date not assessed participant levels of pain-related fear. A more central concern with distraction stems from the theoretical underpinnings of GEXP and exposure treatments in general. As noted above, fearful individuals may engage in safety-seeking behavior during exposure to feared stimuli (e.g., guarding or bracing during movement), effectively diminishing the effect of exposure [79, 141, 146]. In this way, distraction from the emotional and cognitive content of fear comprises avoidance behavior and is not advocated by GEXP. In fact, recent GEXP theorizing has advocated drawing on more experiential treatment options (e.g., Acceptance and Commitment Therapy) to facilitate engagement and tolerance of unpleasant emotions, cognitions, and pain sensations [141, 146].

Importantly, clinical evidence for the use of VR distraction has stemmed almost exclusively from acute pain interventions (e.g., burn dressing) where immediate analgesia is important [60]. However, for many CLBP patients, complete pain relief is rarely an option [78] and patients who persist in “attempting to solve the problem of pain” show poorer outcomes [31, 134, 135]. Although increased physical and social engagement may naturally diminish pain experience through distraction processes (as more stimuli vie for an individual’s attention), the goal of GEXP is to encourage patients to participate in valued life activities despite continued pain experience. Specifically, GEXP aims to break the association between perception of pain and the appraisal of physical harm or damage. Thus the primarily goal of GEXP is not pain amelioration (as that may be impossible), but functional restoration through behavioral engagement [141].

Finally, the historical uses of VR interventions for pain distraction have primarily involved simulations of environments removed from those in which the patient must function. For example, one virtual environment designed for pain distraction, Snow World, has been successfully employed for acute pain management [57, 58] and provides the suffering patient opportunity to experience a virtual world far removed from their current situation. In addition, while these virtual distraction environments often include an interactive component (e.g., shooting monsters; see [27], they typically do not include activities consistent with patient real-life goals and activities of daily living. In contrast, exposure methodologies explicitly aim to situate the patient within contexts where treatment gains would be most useful. In this way, a patient fearful of needles would receive the most gain within a phlebotomy office. Analogously, GEXP encourages patients to practice feared back-straining activities within the contexts they would be most relevant, such as the home or workplace.

In line with the context-specificity of GEXP, a common method applied in the rehabilitation settings (within which GEXP is often executed) employs behavioral observation and ratings of human performance in the real world or via physical mock-ups of functional environments [147]. Persons with motor and/or neurocognitive impairments are observed and their performance is evaluated within artificially constructed home and work environments (e.g., kitchens, bathrooms, offices, factory settings, etc.). Aside from the economic costs to physically construct these environments and to provide human resources to conduct such evaluations, this approach is limited in the systematic control of real-world stimulus challenges and in its capacity to provide detailed performance data capture.

25.5 Treating Pain-Related Fear and Avoidance Behavior in Chronic Pain: Virtual Reality Graded Exposure Therapy

In a recent topical review, Keefe et al. [60] identified and highlighted ways in which VR can be used either alone or in combination with other treatments not just for acute but also for persistent pain conditions. The authors conclude that although research on VR interventions for persistent pain is in its infancy, the use of immersive virtual environments with HMDs hold considerable promise. However, while historical approaches to virtual environments have emphasized HMDs, recent developments in simulation technology have allowed researchers and clinicians greater flexibility in stimulus presentation. Although there are instances where an HMD is still desired (e.g., acute pain management), researchers now have the capacity to provide the user with an ability to interact with digital content using more naturalistic body actions beyond what is possible with traditional VR or game interfaces (e.g., Microsoft Kinect Microsoft [17]; see also Obdržálek et al. [86]). The current trend appears increasingly focused upon full-body interaction for the input in conventional as well as serious games. For the user, this results in an interactive experience in a computer-generated simulation that adapts in a fluid and natural manner with head and body motion [89].

Such emerging simulation and serious gaming technologies are promising tools in many domains of assessment and therapy [90, 93], allowing for body-tracking sensors, multi-modal interfaces, enhanced graphics, cognitive modeling, motor modeling, affective computing, and real-time graphic generation. As noted above, these advances in simulation technologies are not limited to a prescribed approach or hardware configuration. Instead, this new generation of simulation technologies allow for human-computer interfaces that proffer a user experience with multifarious interaction devices and sensory display systems. Stimuli may be presented in a computer-generated simulation for a given user or for multiplayer scenarios.

In the context of interventions for chronic pain, such technological advances have resulted in new possibilities for combining VR exposure treatments, distraction paradigms, and visuomotor processing with validated treatments for chronic musculoskeletal disability—namely, GEXP. At the University of North Texas, we have developed an adaptive virtual environment for treatment of pain-related fear and avoidance behavior. This project brings together a team of researchers to incorporate cutting-edge pain assessment and intervention into a state-of-the-art interactive/adaptive virtual reality graded exposure therapy protocol. As will be described below, Virtual Reality Graded Exposure Therapy (or, VRGET) serves to combine current approaches to GEXP with the innovative Xbox Kinect system by Microsoft.

The Kinect is one of the most widely used whole-body trackers and has the ability to integrate body-state information into various simulations. Further, Primesense's [16] camera and depth sensor allow for full-body interaction. The Kinect system uses image, audio, and depth sensors for movement detection, facial expression identification, and speech recognition. The Kinect's interactive technology allows users to interact with simulations using their own bodies as controls. An important advance in the Kinect technology is that unlike previous attempts at gesture or movement-based controls, the patient is not encumbered by the need to wear accessories to enable the tracking of the user's movements. In this way, the Kinect system represents a perfect tool for the treatment of fear of specific physical exertions (e.g., vacuuming, picking up a child) as it inherently relies on (and captures) an individual's physical output.

The VRGET protocol has been designed to offer an adaptive virtual environment that can be explored by patients under the supervision of a trained clinician. In this way, VRGET offers an integration of a clinician's understanding of exposure therapy with advanced interactive multi-media technology that can be focused on delivering therapy optimized for each patient's individual differences. Individual differences in motivating factors are key to the VRGET protocol. As noted above, GEXP seeks to engage the patient in activities consistent with individually valued life goals that have been interrupted by pain and disability [21, 113–115]. These goals might include being a helpful spouse or a productive member of the workforce [83]. Attention to these goals is critical in the development of an individual hierarchy of avoided activities that is a central component of GEXP [141]. Taking this into account, VRGET systems would allow the clinician to manipulate idiosyncratic motivational factors that are believed to have an impact on the recovery of an individual patient [70].

Despite greater informational output, VRGET enhances patient autonomy during exposure (by placing the exposure interface within the home environment) and decreases the requirement for constant monitoring by the clinician. Rather than clinical observation, VRGET offers potential for automated monitoring and evaluation that can be added to standard clinical evaluation methods. As a result, clinical researchers will have a great deal more data for measuring exposure therapy progress. Of note, the monitoring and data-gathering potential of VRGET systems represents a major advance in detection of minor performance variations and affective changes that are not always sufficiently detectable by standard clinical scales that were constructed based on the human observer. Contrariwise, VRGET systems provide for more focused and high-resolution assessment: increased standardization of administration, increased accuracy of timing presentation and response latencies, ease of administration and data collection, and reliable and

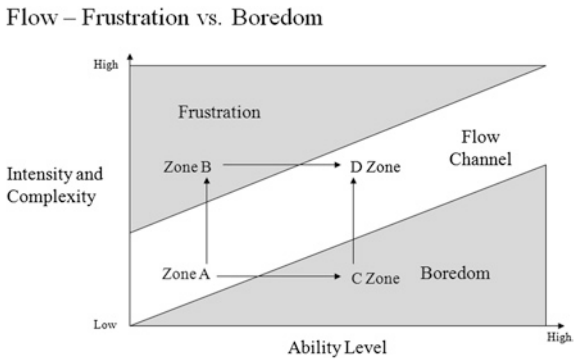

Fig. 25.3 Two-dimensional representation of neuropsychological state

randomized presentation of stimuli for repeat administrations. In short, as a hybrid of clinical intervention and VR technology, VRGET offers the possibility for a new dimension of interactive exposure treatment, bolstering the clinical effectiveness of traditional GEXP by drawing on some of the inherent attributes of the emerging VR technology. Below, we discuss the major potential contributions of VRGET to traditional exposure approaches.

25.5.1 Engagement and Reinforcement

As noted above, participant engagement and retention in treatment has been a major problem for traditional GEXP interventions. However, VRGET can integrate reinforcement contingencies for exposure to feared activities that are not part of traditional GEXP approaches. These additional contingencies (e.g., elements drawn from gaming environments) can add to the reward of activity performance, further solidifying treatment gains. In addition, virtual environments allow for rehabilitation scenarios with novel stimuli and positive reinforcers to increase patient motivation [131]. The motivational potential of VRGET is evidenced by the success of devices like Sony's PlayStation Move and Nintendo's Wii Remote Plus. While these "off the shelf" systems were developed for entertainment, a number of gaming engines have emerged that provide the monitoring and adaptation capabilities needed for use as rehabilitation applications [3, 100].

From a conceptual vantage, the VRET system aims to place the patient into a state of optimal experience, known as "flow," to trigger a broad recovery process (see Riva et al. [108]). According to Csikszentmihalyi [22, 23], "flow" is best understood as an optimal state of consciousness that is characterized by a state of focused concentration during an activity. Following the work of Fairclough [36], we partition the "flow" state of the patient into four quadrants or "zones" (see Fig. 25.3).

Our approach to VRGET uses the assessment and monitoring capabilities of the Kinect sensors to place the patient in the virtual gaming environment at the optimal starting point for that patient (Zone A). It is important to note that we do not conceptualize the flow of the VRGET to be a static experience. A patient's openness to certain movements (e.g., reaching for an object at a 45° angle) tends to be low the first time he or she is immersed in the virtual gaming environment. As the patient's experience of the VRGET protocol increases, his or her fear decreases as a result of successful reaching movements. A potential problem for rehabilitation at this point is that the patient may become bored if the challenge remains constant (Zone C).

Accordingly, as part of VRGET, the challenge will increase, but usually at a different rate than the patient's openness to a new reaching demand. Hence the patient is constantly in a state of flux between the four points shown in Fig. 25.3. At times the patient may begin to disengage (start to experience boredom and move toward Zone C) when the challenge does not increase in pace with his or her skills. At other times, the patient may move toward frustration (Zone B) when he or she is slow to learn the necessary skills. Particularly relevant to Csikszentimihalyi's concept of flow states is Zone B, because it represents a "stretch" zone in which the patient is engaged and his or her ability levels are being increased as they are pushed toward frustration. Fairclough [36] has explained that this state may be tolerated for short periods (e.g., a learning phases and/or a demanding but rewarding period).

25.5.2 Assessment of Emotional Responses to Exposure

Fear is conceptualized as the key emotional component to avoidant behavior patterns. According to the FA model, an individual's fear is based upon the erroneous belief that pain signals physical damage and thus an activity that exacerbates pain (e.g., movement) should be avoided [142]. Theoretically, as patients gradually confront feared activities, maladaptive pain beliefs are challenged and fear responses are extinguished [141]. Prospective tracking of participants' fear responses would thus be central to GEXP intervention. However, current protocols rely only on participant self-report of fear in response to activity. Self-report is notoriously sensitive to a host of confounding influences (e.g., the patients' desire to please their treatment provider).

Knowledge of the user-state during exposure to the virtual environment is imperative for optimal assessment and intervention. Different individuals will invariably have different reactions to the VRGET, and without an assessment tool that can be employed online, the clinician will experience difficulties in identifying the causes of these differences, which may lead to a loss of experimental control or clinical effectiveness. For example, a user may become increasingly frustrated with some aspect of the VRGET protocol, but without proper measurement techniques to detect this frustration while it occurs, compensatory measures cannot be taken. While traditional GEXP offers the capability of presenting a realistic simulation of the real world, online assessment of the user's reactions to that environment is vital to maintaining an understanding of how the environment is affecting the user clinically and to preserving experimental control in a research context.

One answer to these issues and limitations is the addition of psychophysiological metrics to the VRGET platform. The psychophysiological signal is continuously available, whereas behavioral data alone may be detached from the user's experience and assessed intermittently. The continuous nature of psychophysiological signals is important for several reasons. First, it allows for greater understanding of how any stimulus in the environment has impacted the user, not only those stimuli that were targeted to produce behavioral responses [69, 89]. The addition of psychophysiological metrics to the VRGET platform is important because it allows for a continuous objective measure of the user's state, which can include measures of cognitive workload [5], varying stress levels [37, 61] task engagement [103, 117], and arousal [11, 24, 25], among others. Additionally, multiple channels of psychophysiological data can be gleaned from various sensors simultaneously, which further increases experimental control by providing a combination of measures so that one measure alone is not the sole basis for design or treatment decisions [50]. Some limitations that have restricted use of psychophysiological monitoring during rehabilitation interventions have been (a) need for the user to remain stationary, (b) cumbersome wires between sensors and a processing unit, (c) lack of system integration among sensors, (d) wireless communication interference, and (e) absent support for data collection and knowledge discovery [59]. However, innovative technological advances in sensors, low-power integrated circuits, and wireless communication capabilities have allowed for the design of miniature, lightweight, and low-cost wearable psychophysiological sensor nodes [81] that are readily included in the VRGET protocol.

Another approach to assessment of emotional responses is apparent in a number of motion-detection papers that have emerged as a result of the Microsoft Kinect's capability to generate both RGB images and corresponding depth maps of scenes [107, 118]. Kinect's skeletal tracking capabilities have been leveraged for rehabilitation [15], interactive storytelling, video games [124], and social robots [43]. In a novel though limited and unvalidated attempt to assess psychophysiology, Burba et al. [12] used the Kinect to measure the respiratory rate of a person sitting down. It is important to note that the paper mentions problems with tracking when trying to measure the respiratory rate of a person standing. In a more developed study, Martinez and Stiefelhagen [74] used a Kinect-based method to estimate the respiration rate of subjects from their chest movements. They fixed an infrared (IR) dot pattern that could be detected using the Kinect camera with a matching IR filter. The system was evaluated on nine subjects. These preliminary studies may be extended by isolating the chest cavity using more well-developed methods.

Another possible answer to the limitations of traditional approaches to assessing affect with psychophysiological systems is to use the Kinect system for detection based on facial-expression analysis. Researchers have developed regularized maximum-likelihood deformable model fitting algorithms for 3D face tracking with Kinect that allow for optimal use of Kinect's 2D color video and sampling of depth images at 30 fps [13]. Mahmond et al. [72] used Kinect to develop a 3D multi-modal corpus of naturalistic complex mental states, consisting of 108 videos of 12 mental states. Likewise, Zhang et al. [151] have used Kinect and the Facial Action Coding System [34] to collect and establish a 3D multi-modal database for emotion recognition. The resulting database was concluded to be an effective FACS-based model with potential for effective facial-expression interpretation. The Microsoft Avatar Kinect uses facial-expression tracking and arm movements (through skeletal tracking) to allow researchers to control an avatar's head, facial expression, and arm movements. As a participant speaks, smiles, frowns, scowls, etc., her or his voice and facial expressions are recorded and can be enacted by the participant's avatar. Within the Avatar Kinect suite, researchers have access to fifteen unique virtual environments that give context.

Although in the early stages of development, researchers are likewise beginning to make use of the Kinect to monitor emotional body language. There are also projects that explore cultural differences using the tracking offered by the Kinect. In a project focusing on cultural differences and proxemics, Lala et al. [63] focus on the cultural behavior of virtual agents towards each other and to the user. The researchers ensured that each virtual agent followed prescribed social parameters regarding how to react when interacting with other agents. Results revealed that the cultural dimension differentiating individualism and collectivism was mapped to agent characteristics during a series of simulations.

25.5.3 Kinematic Tracking of Movement Performance

In addition to ostensibly avoidant behavior, recent evidence suggests that fear may manifest as altered movement strategy among individuals with CLBP. Persons with CLBP display a variety of biomechanical disturbances [55, 65], including decreased trunk velocity, acceleration, and range of motion [6, 71, 111], as well as alterations in joint coordination [35, 64, 77, 80, 104, 120–122] and muscle activity Hodges [55]. Although such anatomically specific changes are hypothesized to reflect a functional strategy (i.e., to splint/stiffen the spine) in order to enhance protection of damaged tissues shortly after injury [139, 140] continued restriction of motion and abnormal transfer of loads may predispose spinal structures to further damage, possibly contributing to recurrent or disabling pain experience [55, 68, 139, 140]. Research suggests that individuals with high pain-related fear may be particularly vulnerable to develop and maintain protective motor responses. Studies of subacute and chronic CLBP patients show that high-fear individuals show reduced lumbar flexion during bending [40, 130] and maintain guarded spinal motion even as recovery progresses [129]. The latter finding suggests that motor and muscular adaptations to pain may be particularly resistant to extinction, even in the absence of painful stimulation [84]. This continued motor guarding is hypothesized to owe to continued perception of threat associated with movement [84]. A recent investigation by Trost et al. [134, 135] indicated that high-fear participants manifest restricted spinal motion even following an acute experimental induction of low back pain, suggesting differential postural adaptations among high-fear individuals emerge shortly after pain onset and may require intervention at the acute phase of injury.

Traditional GEXP protocols are not equipped to assess for these more insidious motor disturbances in movement performance. The increased metrics of VRGET protocols allow for monitoring of whole sets of dimensions necessary to describe each participant's height, poses, and movements. The building of a skeleton by Kinect requires a depth image of a participant's body and a sensor algorithm to develop an intermediate representation that maps the body [119]. While some parts used to make up the body-map representation are the participant's joints, others are links that connect the joints. These representational parts are coded, and algorithms recognize the codes to assign left and right to sides of the represented body. The Kinect dataset recordings of patient movements can be captured using the OpenNI (http://www.openni.org/) drivers/SDK and are OpenNI-encoded (.ONI). The OpenNI SDK provides a high-level skeleton tracking module that researchers may use to detect and track the captured patient poses and movements. The OpenNI tracking module produces the positions of seventeen joints (head, neck, torso, left and right collar, left and right shoulder, left and right elbow, left and right wrist, left and right hip, left and right knee, and left and right foot), along with the corresponding tracking confidence. The OpenNI tracking module requires initial calibration relative to the patient so that the Kinect can further infer information related to the patient's height and body characteristics. Calibration of the Kinect skeleton requires the captured representation of the patient to remain in a fixed position or "calibration pose" for a few seconds.

With the Kinect's skeletal tracking, clinical researchers can represent a patient's body using a number of points (e.g., joints) representing various body parts: head, neck, shoulders, torso, arms, and legs. Each of these is represented by 3D coordinates. The Kinect uses this information to determine the location and trajectory of all the 3D parameters in real-time, which allows for fluid interactivity. For example, Alexiadis et al. [1] evaluated the performance of a dancer via Kinect-based skeleton tracking. In their study, three different scores were calculated for a dancer's performance, which were subsequently combined to produce an overall score: (1) Joint Positions: a score for each joint was calculated by considering the modulus of the quaternionic Correlation Coeffcient (CC) for each pair of joint position signals. A total score S_1 was then computed as the weighted mean of the separate joint scores; (2) Joint Velocities: an overall score S_2 was extracted based on the velocities of the joints (instead of their positions) by considering the quaternionic CC for the joint velocity signals; (3) 3D Flow Error: for a given frame, the velocities of the joints were considered as 3D motion (flow) vectors. Alexiadis et al. applied the work found in 2D optical flow literature to 3D velocity vectors in homogenous coordinates and calculated the vectors' inner product to obtain a score for each joint [4] and (4) Combined score: the score was calculated as the weighted mean of the above three. This set of the three weights was selected using an optimization approach. In the same manner, the Kinect system can be calibrated to examine whether a CLBP patient is performing activities in a guarded manner, for instance by reducing velocity during certain physical moments or by maintaining rigid postural control during tasks that call for spinal motion.

25.5.4 Generalizing Treatment Gains

As noted above, the generalization of treatment gains from the clinic to the home environment has been a major source of concern for GEXP intervention [141]. As with kinematic adaptations, research has indicated that individuals with high-pain-related fear are hesitant to abandon their appraisals of the harm potential of physical activity. For example, by engaging in GEXP, a highly fearful patient may learn that bending to tie their shoe is safe, but may hesitate to perform similar flexion as part of a different task (e.g., vacuuming) [20, 44–46]. Thus, learning may not transfer from one physical task to another, or to a similar task in a different environment [10]. In short, even with exposure, highly fearful participants are hesitant to change their fundamental belief that movement and pain are unsafe.

Current GEXP protocols acknowledge this limitation [141] and suggest a number of approaches to facilitate generalization of learning across activities and contexts. Specifically, clinicians are encouraged to provide homework to be carried out within patients' home environments and to incorporate multiple stimuli as part of exposure treatment [141]. In addition, a recent study [133] demonstrated that patients can maintain learning effects across a progressively more difficult movement task (rather than across discrete movements). Thus practicing behavior across different environments and creating a gradient of difficulty for discrete activities within an individuals' fear hierarchy are hypothesized to optimize treatment gains. As noted above, the flexibility in simulated environment and maintenance of optimal "flow" engagement offered by the VRGET format further allows variations in grade/degree of exposure that may not be feasible within the constraints of traditional GEXP. That is, treatment "speed" can be optimally graded ("scaffolded") to participant comfort level, thereby facilitating success experiences. After initial orientation, treatment can be monitored and guided in part by the participant, thereby building self-efficacy.

25.6 Conclusions

Virtual reality technologies are increasingly being harnessed for therapeutic and rehabilitative aims both within the physical and psychological domain. Although most of these VR systems are not commercially available (or, are extremely expensive when available), low-cost, accessible systems (e.g., Kinect, Nintendo Wii) are being tested for rehabilitation applications [112]. By virtue of its intrinsically distracting properties and with the aid of HMDs, VR has demonstrated considerable success in the arena of acute pain management [60]. However, as noted above, chronic musculoskeletal pain patients face a number of unique challenges that do not lend themselves well to acute pain treatments, particularly among individuals with high-pain related fear. These challenges have been the targets of interventions guided by biopsychosocial theoretical frameworks. In particular, graded exposure in vivo (GEXP) has emerged among the most successful treatments for individuals most at risk for persistent pain and disability (i.e., individuals characterized by high pain-related fear). By combining VR technology with this empirically validated treatment protocol, we expect that Virtual Reality Graded Exposure Therapy (VRGET) can make major clinical and empirical contributions to the treatment and understanding of chronic musculoskeletal pain conditions.

The flexibility and metrics offered by the Kinect interface are uniquely matched to enhance traditional exposure treatment. Specifically, the noninvasive and interactive format allows for uninhibited physical performance by the participant, which is key for exposure interventions targeting physical performance. This would not be possible using traditional HMD approaches, which can sacrifice ecological validity for immersive distraction. Moreover, by incorporating novel visual cues and gaming elements, VRGET can bolster participant engagement and adherence to an otherwise anxiety provoking intervention. In this way, VRGET capitalizes on elements of distraction that are inherent to VR methodologies without sabotaging the exposure element necessary for treatment gains. Treatment gains can likewise be optimized by the ability of VR simulations to “scaffold” the difficulty of tasks across different contexts. This latter element can address the problem of treatment generalizability demonstrated by the traditional GEXP approach. Finally, the advanced metrics offered by VRGET are useful in at least three ways. First, the system would allow for automated tracking of patient progress and data collection that can be distally examined by a clinician. Second, through addition of psychophysiological measurement or motion tracking, VRGET can examine participant affective response throughout the exposure process; this is particularly key as fear reduction is conceptualized as central to successful treatment. Third, VRGET would allow for tracking of motor responses that are not congruent with successful treatment engagement (e.g., guarding or bracing behavior); such monitoring is not possible within traditional clinical contexts. In summary, VRGET promises to be an affordable and highly accessible treatment option to reduce fear and disability in the context of chronic musculoskeletal pain. Empirical efforts will continue to refine the VRGET methodology toward optimal patient usability and wider dissemination.

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Chapter 26
The Importance and Creation of High-Quality Sounds in Healthcare Applications

Eric Fassbender and Christian Martyn Jones

Abstract In this chapter we look at Audio, a key aspect of virtual and augmented realities that, because of the dominance of the visual sense, is often overlooked in the creation of healthcare and other applications. Audio design and implementation is often under budgeted and considered at a late stage in many projects. This chapter seeks to raise awareness for the importance of high-quality audio in healthcare applications and describes the process of creating quality sound recordings. By way of an example, we describe research that uses nature sounds in conjunction with virtual environments for the purpose of managing stress, pain and other illnesses. We show how noise and distortions can have adverse effects on patient recovery and then describe how to avoid common mistakes in the recording of sounds. We discuss the equipment and workflow that is needed for the production of high-quality sound recordings for use in contemporary healthcare applications.

26.1 Introduction

The cost to the Australian economy of direct workplace related stress was $14.81 billion in 2008 with an additional $10.11 billion caused by absenteeism and presenteeism [1]. Research suggests that stress, and its impacts are increasing, with Australians reporting significantly higher levels of stress in 2012 than the year before [2].

Some strategies that people use to deal with stress include watching TV or movies, spending time with friends and family, drinking alcohol, smoking [2] or playing

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computer games [3]. There can be negative outcomes from these strategies and an alternative to deal with stress may be to go out into nature. There is evidence that being in or looking at images of nature is an effective way to reduce stress [4–7]. However, gaining access to nature and tranquil environments is not always easy, especially for people who live in urban settings. Visiting nearby national parks or nature reserves may offer stress relief, however, the stress involved with travelling to and from these places can contribute to the problem rather than solve it. Using virtual environments to immerse people into peaceful places may offer a solution. While there is little research in using virtual environments for the management of stress [8–12], the findings from this research show encouraging results. For example, [8] found that the use of a virtual relaxation environment "enhances the quality of the relaxing experience" [8] and that using these environments "showed a significant improvement of the emotional state" of study participants ([12], p. 7).

There have been significant improvements in the degree of immersion and the believability of the virtual environment over the past two decades, achieved in part by developments in graphical processing and rendering. However audio is all too often overlooked in the creation of alternative worlds and poor audio can create undesirable disturbances to the experience. This chapter seeks to shed light on this often overlooked aspect of virtual and augmented realities. While this chapter focuses mainly on the production of nature sounds for alternative worlds that seek to reduce pain and stress, the principles presented are relevant for other healthcare applications.

26.2 The Use of Audio and Video in Healthcare Applications

Medical procedures are often associated with discomfort, pain and anxiety. Studies have shown that pain during treatment can be reduced by watching nature scenes, listening to nature sounds or escaping into immersive virtual environments [13–16]. A view of a garden can improve postoperative recovery as well as reduce the amount of analgesics taken by patients [16]. In the absence of windows, sounds and sights of nature displayed on a bedside curtain have been shown to be useful to distract patients from the unpleasant side-effects of for example flexible bronchoscopy, a medical procedure that can cause a lot of discomfort, pain, and anxiety in patients [13]. The imagery in the study by Diette et al. was a static print/photo of a mountain area with a stream shown in the foreground. This visual immersion is limited as the image is static and encompasses only a small part of the patients' field of view. An alternative system with higher levels of visual interest and immersion was developed by Hoffman et al. [14, 15] who used a head-mounted display (HMD) showing a virtual snow world scene. The use of this Virtual Reality (VR) system helped to significantly reduce the pain experienced by patients during treatment of burn wounds [14]. Their findings further show that high levels of visual immersion significantly reduce experienced pain, unpleasantness and time spent thinking about pain as compared to low levels of visual immersion. Actively interacting with the environment is a further positive factor. According to Hoffman et al. the reason for the effectiveness of the immersive VR system is that humans can only process a certain amount of information at any given time and because the VR system requires a lot of attention it leaves “less attention available to process incoming neural signals from pain receptors” [14].

There is evidence that music and sounds can also be used to reduce pain. Cutshall et al. [17] conducted a study that utilised soothing music to significantly reduce pain of post-operative cardiac surgery patients. The study included 100 patients of which 49 patients were administered the music condition. Results show that the music group experienced significantly reduced levels of pain and anxiety, and heightened levels of relaxation as well as overall satisfaction.

Not only can postoperative patients benefit from listening to soothing music. Music therapy has also been found to significantly reduce stress and postnatal depression in pregnant women [18]. Shepley [19] describes a large number of applications where music and access to nature are used successfully in hospital settings to reduce stress and pain as well as to improve patient sleep and recovery [20–26]. Munro and Mount [27] describe the positive effects of using music therapy in palliative care. They conclude that “music therapy has made a significant contribution to a wide variety of palliative care problems” [27].

Williamson [28] used pure nature sounds instead of soothing music. This study investigated the influence of listening to ocean sounds on the night sleep pattern of postoperative coronary artery bypass graft patients after they were transferred from an intensive care unit. Findings showed significantly improved scores for sleep depth, awakening, return to sleep, quality of sleep, and total sleep scores for the group that received the ocean sound treatment. Ocean sounds are also used successfully to help patients suffering from tinnitus [29]. Further evidence for the usefulness of nature sounds in healthcare applications comes from Alvarsson and colleagues who presented 40 subjects with sounds from nature (a mixture of sounds from a fountain and tweeting birds) or noisy urban environments (road traffic noise) after a stressful mental arithmetic task [4]. The results of their investigations suggest that psychological stress and physiological recovery of the sympathetic nervous system is faster during exposure to pleasant nature sounds than to the unpleasant city noises. Ulrich [30] made the same observation with stressed individuals using visual stimuli from nature and urban environments. Those patients who were presented with views of nature experienced a reduction in stress whereas those patients who looked at the urban scenes experienced a significant increase in sadness. Apart from reducing stress, exposure to nature also significantly reduced fear arousal [30].

26.2.1 Effects of Poor Audio in Healthcare Applications

While there is evidence for the usefulness of sound therapy in general, there is little research on the effect of audio quality on healthcare outcomes. One example is [31] who developed the Sonic Cradle, a system that uses participants' breathing to influence sounds that induce a state of relaxation. Their first prototype used sounds very similar in rhythm, pitch and timbre. As the system automatically responded to the breathing of participants, new sounds became unnoticeable because of their similarity with previous sounds. Thus, participants did not feel that they were in control of their experience, and the decreased level of control resulted in a reduction of their level of immersion, satisfaction with the system and ultimately their experienced level of relaxation. Using crowd-sourced sounds allowed for more diversity however some participants found that some sounds counteracted their attempts to relax. A later implementation allowed participants to remove unpleasant sounds, providing a way of "simplifying their sound environment if they feel lost and overcrowded" [31].

Poor audio poses major challenges in the area of distance communication, decision making and online accessibility, and poor audio quality may result in unintelligible information [32]. In telecommunications, low quality and delayed audio causes difficulty for participants to converse [33] and seen in the context of telemedicine, the ramifications of poor and/or delayed audio could be critical. Furthermore, interference noise is a major problem in healthcare situations. Xie et al. [34] describe how noise in Intensive Care Units (ICUs) negatively affects patients' sleep. In a related study one of the highest reported noise levels in an ICU reached 103 dBA [35]. Active sleep was severely reduced and thus the high noise levels would likely affect the recovery of patients in a negative way. Masking of disturbing noises with the sounds of ocean waves has been shown to improve patients' sleep by 37.5 % [28], while sound proofing of a patient's room achieved a noise reduction of 3.3 dB [36].

Research must evaluate the usefulness of immersive virtual realities as relaxation environments to treat workplace related stress and post-operative pain [37]. Sound is an important aspect in this study and in order to create high-quality audio, several things need to be considered. Procedural steps follow for the production of high quality audio for immersive healthcare applications. These are presented in the context of relaxation and recording nature sounds, however the problems and solutions are relevant to other healthcare situations in which sound plays a central role.

26.3 How to Produce High Quality Audio Recordings

There are two main ways to include audio in healthcare applications—purchase/license music or sounds from a vendor (e.g. stock audio website); or produce the music or sounds oneself. Usually sounds from a vendor are of good quality and this option has the benefit that the sounds are readily available at a comparably low price. If the intention is to use nature sounds, the reader may consider nature sounds that are intended as musical compositions (e.g. Chris Watson's Touch Records label, Watson [38]) or pure nature sounds (e.g. [39]) or meditation music. There are also mobile phone applications that allow the mixing of soundscapes (e.g. Back to Nature with Australian Nature Sounds [40]) that could be considered for rehabilitation use. In this context it may be interesting to explore the potentials of using soundscapes as a musical rehabilitation instrument.

Whatever the intention of the reader may be, the benefits of buying such off-the-shelf products are that there is no requirement to purchase costly recording and editing equipment nor is there a need to up-skill in sound recording/editing. However, the choice of music/sounds is limited to the selection of sounds that are offered on the vendor platforms. Thus, sometimes we will not be able to find sounds that match our specific requirements. In these cases we may choose to record our own sounds. In the following sections we will explore the steps and considerations that are required to produce high-quality sound recordings for healthcare applications.

There are many ways to record and edit sounds and it is not the intention of this chapter to compare different methods and equipment. Instead we describe the hardware, software, preparations and workflow that the authors have found to work best for them when developing high quality audio for healthcare. We will look at the technical equipment that is required for recording high-quality sounds, describe considerations that should be made before heading out to the recording location, and then during and after the recording. Finally we will describe the process of editing and cleaning the sounds after they have been recorded. These steps are commonly referred to as pre-production, production and post-production.

26.3.1 Pre-production

To record sound we usually require three central pieces of equipment, a recording device (often called field recorder), microphone(s) and audio editing software. Furthermore, we need access to a computer on which we can install the software as well as a good set of headphones. Ideally these headphones are closed circumaural headphones, which means that they are designed to reduce noise spilling into the headphones from the outside world (other than the sounds that we hear through the microphones). Note that these are not active noise-cancelling headphones but passive noise-reduction headphones. Active noise-cancelling headphones are not suitable for use as sound recording and editing headphones as they can also cancel out wanted sounds. For example, the recordist may intend to record the sound of a train in the distance as ambience for a sound that is more in the foreground. Using noise-cancelling headphones they might not be able to hear the train sounds as the headphones may interpret them as noise to be eliminated.

26.3.1.1 Field Recorder

There are a number of factors that should be considered when acquiring the necessary equipment. Self-noise is one of these factors. It describes the noise that is created by the recording equipment itself and it occurs in the field recorder as well as the microphones. In most situations it is desirable to keep the self-noise of recorder and microphones as low as possible as it may otherwise mask or reduce the quality of wanted sounds. Inexpensive recorders and microphones use cheap parts that in turn produce a lot of self-noise. To avoid such problems one should consider investing in a higher quality recorder and microphones, a combination of which will cost in the range of $1,000–$2,000 AUS Dollars.

Before purchasing these items there are some things that should be kept in mind. Most prosumer and professional microphones require additional external power, so called phantom power. This phantom power is provided by the recorder, however, cheap recorders may provide unstable power to the microphones. For this reason, it is important to invest into a recorder that provides reliable/clean phantom power. Phantom power also has an effect on battery life, thus, selecting a recorder that can deliver phantom power for a longer period of time without interruptions can be important. Headphone levels are another factor as some recorders tend to have a fairly low volume output, which can be a problem because we may not be able to properly hear what we are recording. Lastly, there are size and user-friendliness factors to consider. Depending on requirements and personal preference it may be desirable to have a small field recorder that can fit into one's cabin baggage, however as a generalisation, the smaller the recorder, the smaller will be the buttons and screens. Small recorders will typically also have less functions and features. Furthermore, as a general observation, the smaller units often don't have the space to fit high-quality components, thus, they tend to produce more self-noise than larger recorders. On the other side there are the very large and bulky units, which tend to be the high-end field recorders with 4 and more inputs. While these recorders are usually equipped with very good (i.e. low self-noise) pre-amps (microphone amplifiers), their list of features and menu options can be daunting to anyone but a full-time sound recording professional. The high-end professional recorders are also more expensive than the consumer recorders.

For our purposes we found that a medium (prosumer) recorder in terms of size and features produces recordings that are of very good quality at a medium price point (e.g. Marantz PMD661).

26.3.1.2 Microphone(s)

While most field recorders feature built-in microphones, the quality of these microphones is often fairly poor and only suitable for interviews or recording band rehearsals, i.e. situations where sound quality is not of high importance. However, if one intends to create high-quality recordings, one will require external microphones. There is a large selection of microphones on the market and it can be confusing to understand the differences. Thus, we will briefly discuss the most common types of microphones so the reader may gain a general understanding of the characteristics and type of use for these microphones.

One type of microphone is the **omni-directional microphone**, often simply called omni-mic. These microphones are designed to pick up sounds from all

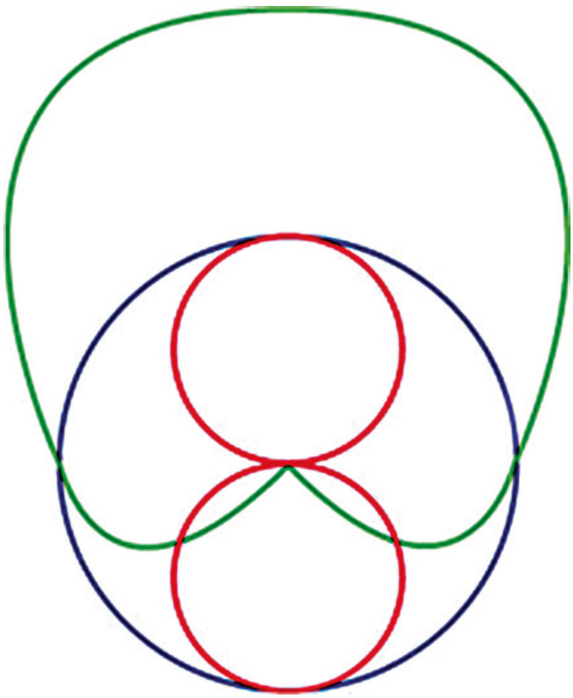

Fig. 26.1 Pick-up patterns of the three most common microphone variations, omni (*blue*), uni-directional/cardioid (*green*) and Fig. 26.8 (*red*) (reproduced from [41])

directions. They tend to have a relatively even, spherical response, which makes them an ideal choice for natural-sounding recordings, however, they often require a lot of amplification and the higher the level of amplification, the higher the level of self-noise. Thus, recordings that are made with omni-mics tend to have a lot of self-noise that is introduced by the amplifiers. The blue diagram in Fig. 26.1 shows the spherical pick-up pattern of an omni-mic. Note that while the diagrams in Fig. 26.1 are shown on a two dimensional plane, the different pick-up patterns are in fact three-dimensional.

While similar in the feeling of ambience and level of detail to the omni-microphones, **uni-directional microphones** record mostly sounds that are in front and to the side of the microphone. They do not record sound that is coming directly from behind the microphone, thus allowing the recordist to select (or exclude) a certain area that they intend to record. The cardioid microphone is the most common of the uni-directional microphones. The green diagram in Fig. 26.1 shows the pick-up pattern of a cardioid microphone. Still, a uni-directional/cardioid microphone will record a chain saw that is 5 km away in the east as well as a frog chorus that is 3 m north, right in front of the microphone. This can be challenging because cardioid mics (like omni-mics) pick up unwanted noise just as much as desired sounds. However, the resulting tracks are often 'full-bodied' recordings that contain a lot of detail and create a good feeling of ambience.

Figure 26.8 or **bi-directional microphones** record sounds in front and behind the microphone, thus making them a good choice if one intends to record room

Fig. 26.2 Field recorder and stereo microphones on tripod, recording bird and water sounds

reflections, however, because of the orientation of the capsules, sounds that are coming from the sides are not recorded at all. The red diagram in Fig. 26.1 shows the pick-up pattern of a bi-directional Fig. 26.8 microphone. Figure 26.8 microphones have a rather small and specific area of application and they are not often used for the general type recordings that one would expect in healthcare applications. Their inclusion in this explanation is therefore only provided for the reason of completeness.

Shotgun microphones are as the name suggests microphones that are very narrowly focused on a recording area in a small angle in front of the microphone. While still picking up some sounds from behind and very little from the sides, these microphones are ideal for situations where the recordist intends to single out a sound and reduce other unwanted sounds. A typical use case for a shotgun microphone is the recording of a single bird in an urban environment. The sound of the bird is amplified while the noise of cars and people surrounding the bird will be reduced. However, shotgun microphones tend to also reduce low-frequency sounds, thus creating recordings that may sound 'thin' and without a feeling of ambience. It is often better to find quiet recording locations, however, if this is not possible, a shotgun microphone recording can provide a good alternative.

For our applications of recording nature sounds for relaxation purposes it was important to create natural sounding recordings, thus we used a technique that uses two cardioid microphones that are arranged in a 110° angle to each other. This orientation simulates the pick-up pattern of the human ears that are more sensitive towards the front than they are to the back. The microphones we use are a matched pair of Rode NT5's. Figure 26.2 shows the combined setup of the field recorder and microphones (in Y orientation or ORTF[1] technique) that were used to

[1] The ORTF technique was named after the French television and radio commission who invented it (Office de Radiodiffusion-Télévision Française).

record morning birds and flowing water in Litchfield National Park in the Northern Territory of Australia. The microphones are protected against wind by so called ‘blimps’ (explained in detail later). Furthermore, the microphones are suspended in U-shaped shock mounts to reduce unwanted handling noise. The unit hanging underneath the microphones is the field recorder that we described earlier.

26.3.1.3 Digital Audio Editing Software

Commonly referred to as Digital Audio Editors (DAE) this group of software applications allows the recording and manipulation of sound, typically on a personal computer. In the present scenario the recording of sounds is performed by using a field recorder rather than a computer and software application, thus, we will only discuss the audio manipulation tasks that DAE’s are typically used for.

The most common manipulation is the fading of sound at the beginning and end of a recording (often called track inside a DAE). A fade-in and fade-out provide a smooth transition of the sound from no volume at the start of a track to the full volume of the track and back to no volume at the end of the track.

Another very common task is the cutting of tracks. This can involve simply cutting out an unwanted bit of recording, however, this most often results in an audible ‘jump’ or click in the track. The more common approach is to create two separate tracks that are then blended together in a second step. DAE’s have many more functions and we will describe some editing tasks specific to our present scenario in more detail later in this chapter. For the moment it is sufficient to know that a DAE is required to edit the audio recordings that are made with the field recorder.

26.3.1.4 Further Considerations

Another aspect for consideration before heading out to the recording location is the choice of recording format. When producing audio we always need to keep the final product in mind and ask ourselves ‘what and who is this recording intended for?’. The answer will determine which format we are going to use during production and as an output at the end of the post-production process. There are a large number of such formats with some of the most commonly used formats being MP3, WAV and AIFF. While MP3 is very widely used and appropriate for most applications, it is a compressed and ‘lossy’ format, i.e. some audio information is lost during the encoding and compression process. While this is not noticeable in most situations, it can become a problem if the original source file was recorded in MP3 and is then edited and saved again in the MP3 format. The problem is that a recording that is already missing audio information (because of the lossy character of the MP3 format) will lose further audio quality if re-compressed. For example, consider a printed page and a photocopy—we can easily recognise the difference between an original high-quality print from a laser printer and a copy of a copy of a copy of the same page.

So in order to create high-quality audio we require a high-quality source file/recording. Both WAV (Waveform Audio File Format) and AIFF (Audio Interchange File Format) formats are designed to provide un-compressed, lossless and high-quality audio files, with WAV having been developed by Microsoft and AIFF by Apple. For the end user they are virtually identical with the small difference that the AIFF format allows ‘tags’ and thumbnail images to be added to the file. On the other hand, WAV is arguably the more widespread format, and the format we adopt for the remainder of this chapter.

Now that we recognise the need to record audio in an uncompressed format (WAV) there are two more things that affect the quality of the recordings—the sample rate and bit depth of the WAV recordings. These two factors greatly impact on the quality of our recordings and getting these right means that we will be able to record high-quality sounds without wasting precious storage space.

The sample rate describes how often per second a sound is recorded. A typical sample rate that is used for Compact Discs (CD) is 44.1 kHz, which means that the sound is recorded 44,100 times per second. The other factor, bit depth, describes the ‘resolution’ of the recording, i.e. how many different volume levels can be recorded. A common bit depth, again for CD’s, is 16 bits, which in the binary system means 2^{16} or 65,536 ‘steps’ at which sound is recorded. There are many possible combinations of sample rate and bit depth. Most often studios will record using at least 96 kHz/24-bit, which will generate large files. However, field recordists may not wish to carry large hard disks to store these files. Instead, for the purposes of most healthcare applications, we recommend to record at 48 kHz/24 bit. Using 24 bits rather than 16 (used by CDs) offers a resolution of 2^{24} or 16,777,216 steps, which is a dramatic improvement over the 16 bit resolution, yet, the increase in file size is still relatively small compared to the improvement in quality. On the other hand, increasing the sample rate to anything beyond 48 kHz (the usual next step is 96 kHz) does not offer an improvement that the average user would be able to hear, however, it greatly increases file size.

Once we have chosen the recorder, microphones, headphones and sound editing software as well as decided on the file format, sample rate and bit depth, we are almost ready for recording. The next phase involves the production of the sound recordings.

26.3.2 Production

It is important to give some thought to the recording location. It may be costly in time and money to travel to a recording location only to find a motorbike race track close by. Thus, a little bit of investigation, e.g. via Google Earth and some informal chats with people who know the area, can save a lot of stress and disappointment. Another factor is the time of year. A forest that may be teeming with life and be full of bird songs in spring may be completely quiet during the other seasons. So it may pay off to investigate the timing of the mating season of a particular species or when food is abundant as animals tend to congregate in these areas during such times. In the Northern Territory of Australia, for example, a good time for bird recordings is in the late dry season because water is more scarce and birds flock to the few water holes that still hold water. For recordings of water flowing in a creek the late dry season may however not be the best time as there is often only a trickle of water left in the water ways. The end of the wet season or middle of the dry season may in this case be the better choice as more water is flowing.

A further aspect is the time of day. Bird life is usually most active in the mornings and evenings, however, recording birds during mid-day allows for a more 'spaced-out' recording, that is, bird songs are more easily distinguishable because there are less bird songs that compete with each other. The time of day (as well as season) also determines how many and what insects are around and whether there will be other people (e.g. tourists, forestry workers, etc.) in the area. While an early morning recording may be desired because of the abundant bird sounds, this is also the time when mosquitoes are very active and because the cardioid microphones that we are using pick up many sounds they will not just record the sounds of the birds but also the buzzing of the mosquitoes. Thus, a bit of preparation may again save the recordist from a lot of frustration, as long clothes and mosquito repellent may be a life-, as well as a recording-, saver.

Further challenges include wind hitting the microphones, flies that buzz around the microphones, human-related noises like chainsaws, cars, barking dogs, airplanes, ticking clocks and mobile phones. Luckily there are solutions to most of these problems. Human-related noises, for example, can mostly be avoided by travelling far from large population areas. Our experience in Australia is that one usually finds quiet recording locations by travelling 2 h by car from a major city, finding a road into a national park and then hiking for another 45–60 min from the last available car park. The end of a road and car park is where most people will stay and few will hike further than 30 min from their parking-/campsite. If hikers still come through the recording area they are usually reasonably quiet as they hike mostly alone or in small groups. Even if such hikers disturb a recording session, they will be gone very soon and a new recording can be started. It is fairly uncommon that multiple hikers/groups interrupt a recording session.

Assuming that we have found a spot with few to no interrupting human-related noises, there are still other factors that can negatively affect a recording. Wind is one of these factors. While our eardrum is suspended and well protected inside and at the end of our ear-canal, most microphones are exposed almost directly to the elements and wind that hits the diaphragm of the microphones creates major disturbances in a recording. For such situations it may be wise to carry what is commonly referred to as a 'blimp' (see grey 'balls' at the end of the microphones in Fig. 26.2). A blimp is a mesh and fabric cage that creates a protective shield around the microphone capsule or the entire microphone. While significantly reducing wind noise, a blimp still allows the desirable sounds to pass through the mesh and fabric, although, small changes of the recorded sound frequency and volume are likely to occur. However, these quality reductions are much less of a problem than the noise that is created by the wind.

Fig. 26.3 A professional windjammer used to reduce wind noise in recordings. *Source* http://www.rycote.com

Depending on the strength of the wind, the blimp alone may not be able to reduce enough of the air that passes through the mesh and fabric and there may still be too much air movement that reaches the microphone and disturbs the diaphragm. In such cases it is necessary to also use a windjammer (see Fig. 26.3). A windjammer (in the industry often referred to as a 'dead kitten') further reduces wind noise by increasing the surface area that the wind hits and thus dispersing the force of the wind into multiple directions. The downside of a windjammer is that apart from reducing wind noise, it also muffles the desirable sounds. However, the muffled sound is likely preferable to wind noise, which can ruin a sound recording completely.

Other challenges mentioned earlier are mosquitoes and/or flies that buzz around the microphones. Unfortunately, both types of insects are very attracted to humans and the furry windjammer. However, having the sound of mosquitoes and flies in a recording can be very disturbing because quite often they will fly directly around the microphone and because of their close proximity to the microphone their sounds appear much louder in the resulting recording than, for example, the sounds of frogs in the distance. As may be obvious, the high-pitched sound of a buzzing mosquito in a recording for relaxation may not contribute to participants' ability to relax. A solution to this problem may be to use insect spray, however, the chemicals in these sprays are very likely to permanently damage the equipment (e.g. dissolving plastic), thus we do not recommend this approach. One way to address the insect issue is by using a mosquito or fly net that is draped over a pocket umbrella and holding this net over the microphones, effectively keeping flies at a distance where their sounds are much less obvious. The umbrella can in fact double as sun or rain protection in adverse climatic conditions.

However, even with all these precautions and protective measures, there are still factors that can negatively affect a recording. One of these factors is the recording level. Sound volume is measured in Decibel (dB) with a whisper registering at about 15 dB and a jet engine around 140 dB of sound pressure. In the sound recording discipline dB is used in a slightly different way in that the highest volume level at which a sound recording device can record a sound without distortion is defined as 0 dB. Thus, 0 dB acts as a reference point. Most recording devices have displays that show this point at the upper end of the volume scale. Most often this point is marked by a red dot or area indicating that the recording level is too high. If the recorder is operating in this area it is recording the sound with distortions. These distortions are commonly referred to as ‘clipping’ because the recorder ‘clips’ every sound that goes above the 0 dB level. Thus, recording at 0 dB is undesirable because audio information will be lost and sound distorted.

Most recorders will use a colour (orange/yellow) to indicate sound levels above and between −10 and 0 dB. This area is a buffer zone that allows for sudden and unexpected loud sounds (e.g. a lightning strike). An ideal sound recording level would be between −20 and −10 dB as this is a ‘safe’ area where the recorder will clearly record the sounds without any distortions. During the sound check the scale should only go very rarely and only during the loudest sounds into the orange/yellow zone of −10 dB and above. By doing this we are reasonably safe that even if an unexpected loud sound appears (a bird that lands and begins singing in a very nearby tree) we still have some ‘headroom’ that will capture this loud sound without distortions.

Once the microphones and recorder are set up and recording volume levels are adjusted we are almost ready to hit the record button. The only remaining step is to adjust the headphone output volume to a level that is desirable for the recordist. Most often this would be a volume that is similar to the volume that we would hear if we were not wearing headphones, however, sometimes it can be desired to hear more than what we would normally hear. Thus, increasing the headphone levels to a higher volume can help us to record sounds that we would not be able to hear with our normal hearing. To adjust headphone levels we will need to put the recorder in ‘Pause’ mode as this is the preparation step before recording. We listen to the sounds through the microphones, the recorder and the headphones, however, we are not recording yet. The pause mode allows us to adjust settings until we are confident that the recording levels and placement of the microphones will properly capture the sound that we intend to record. Once we have done all this we can finally hit the record button and listen to the sounds that we are recording.

At the end of a session we simply press the stop button and depending on the recorder, the recorded track will be saved on an internal or external storage medium (Hard-Drive, Secure Digital card, Compact Flash card, etc.).

26.3.3 Post-production

After returning from the recording session we transfer the recorded tracks onto a personal computer for post-production. This usually includes editing of the tracks to remove unwanted sounds and saving the edited track in another format. For example, it is quite common that while recording and editing is done with

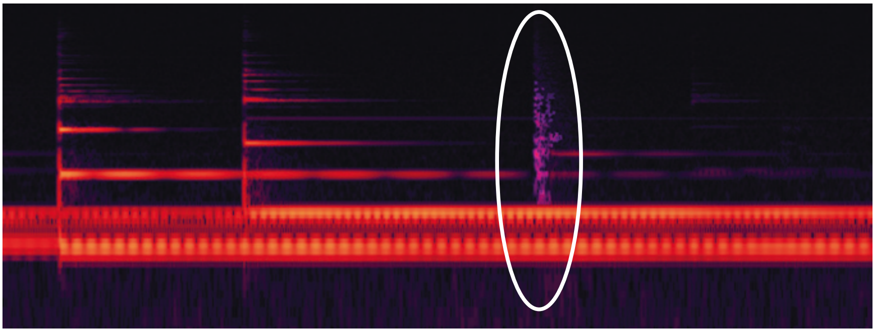

Fig. 26.4 A sound recording with a noise artefact inside white ellipsoid (digitally emphasised for better visibility)

high-quality WAV files, the final track will be exported as a MP3 file. This is especially the case if the track is intended for use in a software application. The simple reason for this is that MP3 can take up only about 10 % of the storage space that a WAV file requires and at the final implementation point, the reduction in quality is not audible to the end user anymore.

26.3.3.1 Editing

There is a large selection of Digital Audio Editing (DAE) software applications available on the market, from free tools such as Audacity to commercial products such as Pro Tools, Cubase and Wavelab. The DAE we use for our purposes is Adobe's Soundbooth (replaced by Adobe Audition in 2011). The techniques described hereafter will be very similar in other DAE's.

One of the most common editing tasks is the trimming of recordings. In most cases the tracks will have some unwanted handling noise from pressing buttons or touching the equipment at the beginning and end of a track and trimming simply means removing these unwanted bits of recording. If the remainder of the recording does not have any more disturbing noises then the editing process is finished after the trimming and we can export the track to the desired format. However, in most cases there will be other sounds that the recordist/editor will want to remove. This can include the beeping of a car security system from a nearby car park or a mobile phone unintentionally going off. Figure 26.4 shows a spectrograph of a recording of wind chimes. A spectrograph gives the recordist/editor a better representation of an audio track than a simple waveform display. While a waveform display shows the change of volume levels for all audio frequencies combined, a spectrograph shows the volume levels for each frequency. The below figure shows the 8 or so major frequencies that a wind chime produces, starting at around 300 Hz and going up until about 10 kHz. The brightness of the orange coloured areas expresses the volume level. The more yellowish the orange is, the louder that particular frequency is in the spectrum of frequencies.

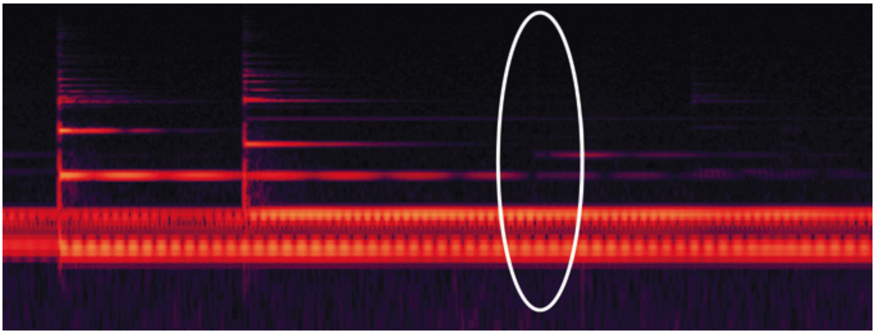

Fig. 26.5 The same sound recording with the noise artefact removed (digitally un-altered)

The white ellipsoid shows another type of unwanted noise in a recording. In this case, while recording the wind chimes inside a house, the wood in the roof creaked as it was expanding by the warming of the sun. There were multiple of these noises in the recorded track and one editing strategy would have been to remove the entire section where the creaking was audible. However, in some cases the removal of such sections can lead to audible breaks in the audio where the listener will perceive that a part of the audio track has been removed. In these cases it is better to either cut the track into two separate tracks and slowly blend them back together into one track (explained in detail later) or try to repair the section in question with a tool that 'heals' the sections automatically. Such a repair function is available in Soundbooth and is particularly useful if a recording has multiple positions with interrupting noises as it can be tedious to cut and blend the separated tracks multiple times otherwise. Figure 26.4 shows a position in the wind chimes track where a creak from the roof appeared. The interfering noise artefact is digitally emphasised for better visibility. The ellipsoid in Fig. 26.5 shows the same section of the wind chimes track where the interfering noise has been removed after the auto heal feature has been applied. The resulting track is a clean, high-quality audio recording.

As mentioned above, another strategy would have been to simply cut out the section in question. While this does not work well in tracks with a lot of volume changes across different frequencies (like the wind chimes which become softer very quickly), this strategy works very well for recordings of sounds that have few different sound sources and little change in volume. A recording of a gently gurgling creek is a good example of a recording where simply cutting out a section will cause little problems in the resulting track. Because the sounds are so similar before and after the cut, our ears and brain do not notice that a part of the recording is missing. However, when performing such a cut and remove action, one should pay close attention to the overall sound level and select a cutting point where the volume level is at 0 dB. If we were to instead cut at a 'high' point on one side and a 'low' point on the other, the resulting track will have a very audible click. Thus, when cutting out a section from a recording it is important to find positions on both sides of the cut where the sound level crosses from

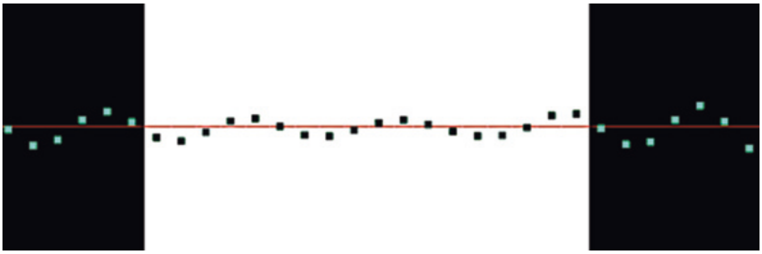

Fig. 26.6 A section that is to be removed from a recording. Cut points are positioned where the sound wave crosses the zero volume level

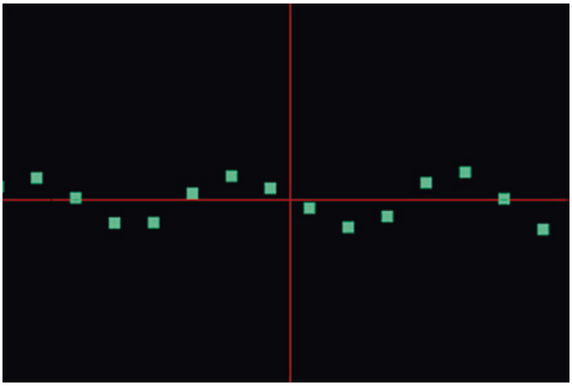

Fig. 26.7 The same location after the highlighted section has been removed. The sound wave continues without interruption

the positive to the negative side of a sound wave. This point is called the zero crossing. Figure 26.6 shows a section that is selected for removal. Note how on the left side we have selected a cutting point where the sound wave moves from the positive volume towards the zero crossing and on the right side we have selected a point where the sound wave leaves the zero crossing and moves into the negative volume area. Figure 26.7 shows the same track with the red vertical line indicating where the highlighted section has been removed. The sound wave moves from positive volume to negative volume without a visible (and audible) jump.

It should be noted that nature sounds are often very forgiving when it comes to cutting out small sections, i.e. the listener will not normally perceive that sound has been removed. However, when the amount of cut material is too long and there are too many different sound sources in one track (e.g. flowing water, crickets, birds), the recorded soundscape often changes too much and we will need to create separate tracks and blend them back into one track. Figure 26.8 shows a track that has been separated into two tracks. Figure 26.9 shows how the end of Track 1 is faded out and the beginning of Track 2 is faded in at the same time. It takes a bit of practise to adjust this cross-fade so that the overall volume level remains constant, however, in most cases this is a relatively straightforward task. Once the two tracks have been arranged so that they blend into each other without any disturbance, they can be exported as a new, single track. The disturbing sound has

Fig. 26.8 One track that has been separated into two tracks

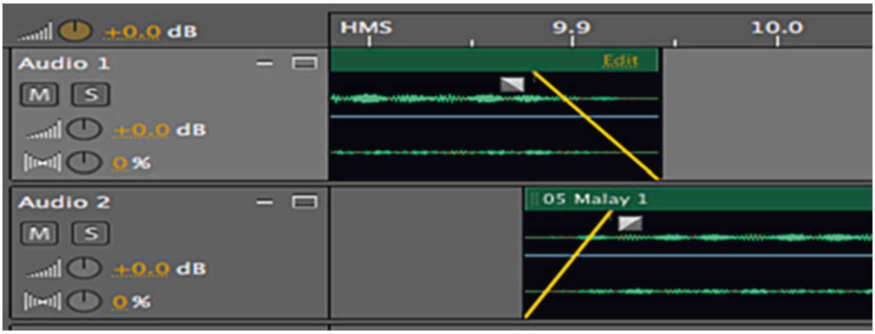

Fig. 26.9 Track 1 is faded out at the end and track 2 is faded in at the beginning

been removed and the listener will not hear any clicks where the section has been removed.

After the unwanted noises have been removed with either auto heal, straight cut, or track blending, the remaining steps are mixing, mastering and export.

Mixing and mastering are only required if multiple tracks are exported for the same use case scenario. This can for example be the release of a CD music album or for use in a healthcare (or other) software application. In these cases it is important that all tracks have similar volume levels because otherwise the listener would need to adjust the volume level from one track to the next. One way of achieving a uniform volume level across all tracks is to 'normalise' the tracks. During normalisation the software searches for the loudest part in a track and adjusts the volume level of the entire track until the loudest part reaches the 0 dB threshold that we mentioned earlier. However, some tracks may have a large dynamic range (difference between soft and loud sections) and some tracks of the same album may have a small dynamic range. In these cases it is more useful to manually adjust the volume levels of all tracks until their perceived volumes are equal to each other. Once volume levels are adjusted the last step is the export of the track(s). The export format varies depending on the use case/application for which the recordings were produced. For a CD project, we would export the tracks as 44.1 kHz/16 bit

WAV files. For a software/healthcare application it is appropriate to use 256 kbit/s or 192 kbit/s MP3's. If an application features only spoken dialog, 160 kbit/s or 128 kbit/s MP3 s may be sufficient, however, sound quality should be checked as distortions may negatively impact on the effectiveness of a given healthcare or other application.

26.4 Summary

At the beginning of this chapter we discussed the effects of stress on health as well as a number of alternative strategies that are known to help reduce stress. Some of these strategies include looking at nature scenes and listening to nature sounds. Where direct access to nature is not possible, the use of recorded audio/visual material can help patients reduce stress and post-operative pain. Some solutions include virtual environments that display an alternative world to distract patients from their pain. Music therapy is another strategy that has been found to help patients with sleep and post-operative recovery, however, low quality sounds as well as interfering noises are shown to reduce the effectiveness of these therapies. To help healthcare practitioners to create sounds for their applications we described the process of recording and editing high quality nature sounds.

Immersion into an alternative world can provide health improvements, however low quality audio or noise in healthcare applications are distracting and counterproductive. While the effects of poor and delayed audio have been investigated in the area of business meetings, there are no studies that investigate audio quality against health outcomes. Audio applications promise to help patients with e.g. sleeping problems, yet quite often the recordings are of low quality, artificially created or loop every few seconds. It is therefore important to investigate how these factors affect patients' conditions and to design, develop and create high quality audio for future healthcare settings.

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