Rainer M. Holm-Hadulla
Joachim Funke
Michael Wink *Editors*

Intelligence – Theories and Applications

Springer

Intelligence - Theories and Applications

Rainer M. Holm-Hadulla
Joachim Funke • Michael Wink
Editors

Intelligence - Theories and Applications

Springer

Editors
Rainer M. Holm-Hadulla
University of Heidelberg
Heidelberg, Germany

Joachim Funke
Department of Psychology
University of Heidelberg
Heidelberg, Germany

Michael Wink
Institute of Pharmacy and Molecular Biotechnology
University of Heidelberg
Heidelberg, Germany

ISBN 978-3-031-04197-6 ISBN 978-3-031-04198-3 (eBook)
https://doi.org/10.1007/978-3-031-04198-3

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

“Intelligence: Theories and Applications” focuses on a characteristic that we find in living beings of all kinds: the capacity to adapt to different environments. Intelligence has made humans a successful species over thousands of years. But will it stay that way? Ecological problems, wars and pandemics threaten humankind. Artificial intelligence (AI) now seems to be superior to human intelligence in some respects. Are humans in danger of being ousted by AI? These topics call for a multi- and interdisciplinary approach.

This multi- and interdisciplinary view derives in the present volume from the wide range of perspectives represented by a comprehensive university. Authors from the natural sciences and medicine, the humanities, and cultural studies discuss their understanding of intelligence from different perspectives and based on different research methods. In addition, there are external contributions that underline the social relevance of the phenomenon. These contributions address very different aspects of the general topic and thus ultimately achieve an interesting diversity of aspects. In their introductory chapter, Rainer M. Holm-Hadulla and Hannes Wendler take on the task of summarizing and classifying a variety of different perspectives on intelligence and advance an integrative model of its concept Back in 2000, one of the authors already curated an exciting yearbook on the topic of “Creativity” (Holm-Hadulla, 2000).

The contributions to this volume of the *Heidelberg Yearbook*, which has existed since 1805, are presented here in keyword form:

In their introductory chapter “The Evolution of Intelligence: A Multi- and Interdisciplinary Review of Concepts and Practical Applications,” *Rainer M. Holm-Hadulla* (medicine, psychiatry and psychotherapy) and Hannes Wendler (philosophy, psychology) indicate the deep structure underlying the individual contributions and discuss the ways in which they interconnect to an integrative concept of intelligence.

The articles are listed here in alphabetical order (in the volume itself, they are grouped under the seven headings set out in the Introduction).

Ines Al-Ameery-Brosche and *Franz Resch* (child and adolescent psychiatry) point out in their contribution “Emotional Robotics: Curse or Blessing in Psychiatric

Care" the dangers as well as the advantages of "social robots" and medical IT applications, which can be seen as tools but not as substitutes for human attention.

Theresia Bauer (minister for science, research and the arts of the state of baden-Württemberg, Stuttgart) provides a practical report from the world of political action in the chapter "Political Intelligence? A view from practice between politics and science." Wisdom and trust in science play an important role here.

Michael Byczkowski (SAP) and *Magdalena Görtz* (urology) write on "The Industrialization of Intelligence," using medical examples to show how the interplay of observation, experience, cognition, and skills leads to intelligent insights.

Andreas Draguhn (physiology) describes the "Neurobiology of Intelligence" and deals with an essential biological correlate of intelligence: the brain. Important framework conditions for genetically based "biological" intelligence show that good physical conditions, diverse stimuli, and conducive social interactions in the first years of life are favorable for its development.

Claudia Erbar and *Peter Leins* (biology) take an evolutionary perspective in their article "Intelligent play with chances and selection" and use numerous examples to show intelligent constructions of evolution as they are used today by bionics.

Klaus Fiedler, *Florian Ermark,* and *Karolin Salmen* (social psychology) use the term "metacognition" to outline potential errors and deceptions in rational judgment and decision making in the fields of law, medicine, and democracy. Quality control applied to one's own thinking is called for.

Dietrich Firnhaber (Covestro AG, Leverkusen) takes a close look at strategic planning for dealing with uncertain facts in his article "Intelligent handling of complexity by companies." He shows that uncertain knowledge about known uncertainties can be used productively.

Thomas Fuchs (philosophy and psychiatry) concludes in "Human and Artificial Intelligence: A Critical Comparison" that human intelligence is something specifically human that cannot be placed on the same level as artificial intelligence, i.e., algorithm-driven machine data processing.

Joachim Funke (general psychology) describes in "Intelligence: The Psychological View" different conceptions of the construct and at the same time points out its "dark side," i.e., the destructive potential of intelligent action.

Sebastian Harnisch (political science) takes a look at the concept of "political intelligence and wisdom." The historical roots of these concepts are set out, as are current developments in the twentieth/twenty-first century.

Sabine C. Herpertz (psychiatry and psychotherapy) distinguishes in her chapter on "Interpersonal Intelligence" between mentalization, empathy, and caring. She describes their neurobiological correlates and draws practical consequences.

Vincent Heuveline (mathematics) and *Viola Stiefel* (computing centre) describe in their contribution "Artificial Intelligence and Algorithms: True Progress or just Digital Alchemy?" the basics of AI and the limits of its possible applications. They advocate improvements in AI competencies, e.g., in the school sector, and at the same time sensible and sensitive handling of AI from ethical and ecological perspectives.

Thomas W. Holstein (molecular biology) assumes that the entire cellular and molecular repertoire of our nervous system was already formed in earlier evolutionary stages over 500 million years ago. The ability of neuronal systems to carry out cognitive decision-making processes enables associative learning and intelligent problem-solving even in organisms that we consider to be simple, such as marine snails. Specific genes play a central role in this process. Comparative genomic studies make a decisive contribution to the understanding of brain evolution.

Magnus von Knebel Doeberitz (tumor biology) presents new possibilities for artificial intelligence in the field of medicine. Many current advances in medicine would not be possible without AI. He supplements the *Internet of Things with* an *Internet of Medicine*.

Katajun Lindenberg and *Ulrike Basten* (child and adolescent psychotherapy) describe from a clinical perspective the "Development of intelligence in relation to the use of digital media." Given the increasing use of digital media by children and adolescents, the advantages and disadvantages for their mental development are discussed here in the shape of an overview article.

*Vera Nünning (*cultural studies) takes up our framework topic in her contribution "Intelligence in and with Literature" by analyzing its representation in two recent novels by Ian McEwan and Kazuo Ishiguro, thus making the powerful experiential world of literary writing comprehensible for the understanding of self and world.

Manfred Oeming (theology) makes clear in his contribution "Intelligentia Dei" the science-friendliness of the Bible. On the other hand, he warns against too much faith in technology and the "promises of salvation" held out by some apologists of artificial intelligence.

Gudrun A. Rappold (genetics) describes what happens "when intelligence is impaired." Using autism as an example, she illustrates genetic mechanisms that negatively influence the development and function of neuronal networks and circuits but are also susceptible to treatment if detected early.

Robert J. Sternberg (cognitive psychology) in his article "Meta-Intelligence: Understanding Control, and Coordination of Higher Cognitive Processes" asks whether various higher processes of cognition cannot be grouped under the umbrella term "meta-intelligence."

Thomas Stiehl and *Anna Marciniak-Czochra* (mathematics) deal with the topic "Intelligent algorithms and equations? - An approach to the intelligence of mathematical concepts" and indicate analogies between human intelligence and the intelligence of learning algorithms. The parameter estimates and the resulting predictions achievable with computer simulations make complex issues manageable.

Christel Weiss (medical statistics) outlines in her historically oriented chapter "Statistics and Intelligence: a Changing Relationship" the development of statistical methods in the context of "measurement of intelligence" and also deals with the intelligence of data, methods, users, and consumers of statistics.

Michael Wink (biology) looks at "Intelligence in Animals" and provides many examples of intelligent behavior such as hammering, fishing, and poking. Animals are capable of amazing cognitive feats (problem-solving, cognition, memory and orientation, etc.) and of social behavior.

We would like to thank Hannes Wendler for his assistance with the manuscripts.

Heidelberg, Germany
Spring 2022

Rainer M. Holm-Hadulla
Joachim Funke
Michael Wink

Reference

Holm-Hadulla, R. M. (Ed.). (2000). *creativity* (Heidelberger Jahrbücher Vol. 44). Springer.

Contents

About the Editors

Rainer M. Holm-Hadulla, MD is a professor of psychiatry, psychosomatic medicine, and psychotherapy at the University of Heidelberg and the Universidad de Chile, among others. He also works as a counsellor and training psychoanalyst (IPA). In his functions as a professor and as a clinician he was confronted with various forms of intelligence and creativity. He reflected his experiences under neuroscientific, psychological and cultural perspectives in several German books: "Creativity – Concept and Life-Style," "Creativity between Construction and Destruction," "Passion – Goethe's Path to Creativity" (available also in English, Spanish, and Italian), "Integrative Psychotherapy" (also available in Italian and English with the title "The Recovered Voice – Tales of Practical Psychotherapy"), "The Art of Counselling and Psychotherapy" (available in English and Spanish).

Joachim Funke has been Professor of general and theoretical psychology at the Psychology Department of Heidelberg University since 1997. He received his doctorate from the University of Trier in 1984. In 1990 he worked on his habilitation at the University of Bonn. Funke has been a visiting professor at various universities, including Fribourg (Switzerland), Melbourne (Australia), Nanjing (China), and Szeged (Hungary). His primary research interests include thinking, creativity, and problem solving. Funke has published numerous articles in international journals, contributed chapters to textbooks, and edited and published his own books. From 2010 to 2014, he served as chair of the International Expert Commission on Problem Solving in the OECD's global PISA studies. He is credited with a shift in the understanding of problem solving that changes the perspective from static to dynamic problem-solving activities. In 2015, he was awarded an honorary doctorate by the Hungarian University of Szeged for his contributions to the computer-based assessment of problem-solving processes. From October 2011 to March 2019, Funke served as speaker of the university's Academic Senate. His retirement began in April 2019.

Michael Wink is a full time professor of pharmaceutical biology at the University of Heidelberg, where he has served as the head of the Biology Department at the

Institute of Pharmacy and Molecular Biotechnology since 1999. He has been working as a senior professor at Heidelberg University since late 2019. After studying biology and chemistry at the University of Bonn, he conducted research in Braunschweig, Cologne, Munich, and Mainz. His fields of work range from phytochemistry, medicinal and poisonous plants, ornithology and natural treasures to systematics, phylogeny, and evolutionary research. He is extensively published, as an author/co-author of more than 20 books and over 1000 original papers. He is a visiting professor at universities in China, Thailand, Argentina, and Mexico, as well as a member of various scientific advisory boards, editor of several journals, and recipient of several awards.

Chapter 1
The Evolution of Intelligence: A Multi- and Interdisciplinary Review of Concepts and Practical Applications

Rainer M. Holm-Hadulla and Hannes Wendler

Abstract Intelligence enables us to understand events and to shape our environment. It is a heterogeneous ability, and in the following we shall be discussing various attempts undertaken by individual scientific disciplines to define and explain it. In our outline of the evolution of intelligence, one major focus is on interdisciplinary connections, a focus that can be expected to deepen our understanding of the subject (especially with regard to its practical consequences). In our multidisciplinary approach to the evolution of intelligence, we identify several levels of intelligence. The higher levels are grounded in, and built on, the lower levels, with respect to which they not only increase in complexity but also display differences in kind. (1) Biological intelligence is concerned with vital processes and the co-adaptive interplay of an organism and its environment. (2) Psychological intelligence encompasses various faculties (cognition, emotion, efficacy, etc.) at the level of the individual person and is not identical with "what the intelligence test measures" (as the operationalist position would put it). (3) Mathematical intelligence attempts to model and describe intelligence in formal terms. (4) Artificial intelligence is concerned with the synthetic or virtual re-creation of known models of intelligence and, similar to biological forms of intelligence, sheds comparative light on the specific nature of human intelligence. (5) Cultural intelligence designates ways of relating to the world that are sedimented in creative products and catalyze intelligent acts of an individual nature. (6) Political intelligence (and political wisdom) refer to holistic

Our sincerest thanks go to Andreas Draguhn, who provided extensive, concise and – last but not least – critical comments on this article. The quality of the section on biology and the overall clarity of the text have profited especially from his clear-sighted remarks.

R. M. Holm-Hadulla (✉)
University of Heidelberg, Heidelberg, Germany

Universidad de Chile, Santiage de Chile, Chile
e-mail: rainer@holm-hadulla.com; https://www.holm-hadulla.com/

H. Wendler
a.r.t.e.s. Graduate School of the Humanities, Cologne, Germany
e-mail: wendler@phi-psy.de; https://www.phi-psy.de/

R. M. Holm-Hadulla et al. (eds.), *Intelligence - Theories and Applications*,
https://doi.org/10.1007/978-3-031-04198-3_1

deliberation and practical decision-making, i.e., coming to terms with the complexity of our life-world and responsibly engaging with it and its inhabitants. Viewing intelligence against the backdrop of these six levels in its evolution foregrounds the fact that any true understanding of each of these forms of intelligence must pay due heed to the other varieties. The same rationale holds for the practical application of intelligence.

1 Introduction

The first issue of *Nature*, still one of the leading scientific journals of our time, begins with an aphorism attributed to Goethe: "Nature! We are surrounded and embraced by her: powerless to separate ourselves from her, and powerless to penetrate beyond her … She has neither language nor discourse but she creates tongues and hearts by which she feels and speaks." (Huxley, 1869, p. 9). In this same vein, scientists from various disciplines attempt to describe and understand the nature of intelligence with "tongues and hearts," i.e., as a human property.

The term "intelligence" is a term used equally in scientific and everyday language. It comes from the Latin "*intelligentia*," which can be translated not only as "insight" or "understanding" but also as "connoisseurship." The term contains the verb "*legere*" which means "to gather, collect, select, choose". Finally, "*intellegere*" can be rendered as "to perceive, recognize, see, realize, understand, comprehend." Thus, the term refers to a variety of mental processes, behaviors, and interactions. We suggest that intelligence occurs at different levels that are the domain of different scientific disciplines and perspectives. However, these levels are not only hierarchically organized but permeate each other, necessitating an interdisciplinary concept of intelligence. Let us begin with the first level of intelligence regarded from the vantage of the natural sciences.

2 Biological Foundations

From a modern scientific perspective, humans no longer appear to be the only species that possesses intelligence. Cognitive abilities worthy of the name are attributed to other species such as primates, whose brains exhibit significant similarities with those of humans. However, creatures without a brain mantle (neocortex), such as carrion crows, can also solve tasks intelligently and do no worse in this respect than apes (Nieder et al., 2020). Recent studies even attribute intelligence to cephalopods (Albertin et al., 2015; Godfrey-Smith, 2016; Schnell et al., 2021). This suggests that the evolutionary development of powerful brains began at an early stage indeed. The common genetic, molecular, and cellular constituents of nervous systems took shape more than 500 million years ago (Holstein, this volume). Consequently, a true understanding of the diversity of brain architectures requires comparative approaches in the field of *genomics* that reflect the divergent evolution of existing species (see, e.g., Mao et al., 2021). In line with the widely stratified character of intelligence, such studies must however be supplemented by anatomical, physiological, behavioral, and cognitive approaches (Dicke & Roth, 2016; Hofman, 2019).

Current neurobiological findings show how different brain architectures (and hence behavioral–cognitive abilities) have evolved as a response to different niche requirements and environmental constraints. This is visible even in rather simple neuronal systems arising from the same basic cellular elements—electrically active neurons—as complex brains (Holstein, this volume). Networks formed by interconnected neurons form a material substrate for the cognitive decision-making processes underlying associative learning, behavioral flexibility, and "intelligent" problem-solving. This holds even in what we consider to be simple organisms, such as the sea snail *Aplysia californica* (Kandel et al., 2000). The relatively small number and large size of the neurons these animals possess make them excellent subjects for detailed studies of the biological, chemical, and physical processes associated with cognitive performance. However, analytic methods at the cellular and molecular level alone cannot explain the specific properties and cognitive–behavioral function of neural systems and the *emergent* functional properties they develop at the levels of networks, nervous systems, and organisms (Holstein, this volume).

One major principle governing the evolution of organisms is that of natural selection, i.e., higher differential reproduction of those conspecifics that are better adapted to the respective environment—so-called fitness (Darwin, 1859; cf. Mitchell, 1987). To a certain degree, however, human intelligence has emancipated itself from this principle, because it is also subject to cultural evolution, a process which is, in turn, heavily influenced by human intelligence itself, resulting in a circular process of self-adjustment of the evolutionary forces operative in human development (Tomasello, 2009; Deacon, 2012). This is most evident in the development of art, ethics, and morals. We will come back to this later. Drawing on Darwin's evolutionary optimization principle, Erbar and Leins (this volume) show that even plants make use of an evolutionary "box of tricks." Plants can imitate, deceive, and kill, although there is no evidence for the involvement of any genuine cognitive processes, let alone conscious intention, in what they "do." In fact, it is the flexible adaptation of plants to their environment that gives rise to apparently tailor-made reactions that are sometime called "intelligent" (Erbar & Leins, this volume). They are not, however, rooted in complex representations and cognitive operations within a nervous system. Scientific disciplines like bionics learn from this natural "box of tricks," which helps them to build complex technologies from robotics to artificial intelligence.

Animals, especially those with high behavioral flexibility, exhibit genuine intelligence (Wink, this volume). Many species recognize causal relations, make plans, and find unprecedented solutions. This is particularly evident in the use of tools. Some examples of tool use are genetic, others are acquired, and for the most part "nature" and "nurture" go hand in hand. Not only apes but also other species such as birds have social networks through which they pass on their practical knowledge to conspecifics. Even though tool use demonstrates that such animals are capable of abstraction, generalization, problem-recognition, and problem-solving (Wink, this volume), it seems hardly possible for them to think at the same level of abstraction as humans, i.e., to create abstract theoretical constructs, ethical, scientific or religious systems, or to philosophize. To the best of our knowledge, no species other than humans construct models designed to explain themselves and the world (see below).

However, even the most sophisticated forms of human thinking are limited by natural conditions, as we can see from the cognitive and behavioral consequences of brain disorders. Though neuroscience has made great progress in defining the natural conditions of intelligence, we are still far from understanding them completely. Physiologist Andreas Draguhn proceeds from this definition: “Intelligence is the ability to solve problems through flexible acting or thinking. Acting and thinking are meant, here, as intentional acts that go beyond purely reflexive automatisms, i.e., as actual agency” (Draguhn, this volume). The adaptation of a living being to its habitat is not sufficient to qualify as intelligence. Only living beings that can actively choose between alternatives can be regarded as intelligent. This form of intelligence is bound up with a central nervous system which, in turn, is made up of the same elements and mechanisms as simpler brains.

Draguhn emphasizes that there is no straightforward answer to the question of how pronounced brain development in hominids came about in the course of evolution. Hofman (2019) summarizes the physical and socio-cultural conditions of this development. New developments in environmental conditions such as climate changes and food scarcity elicited constant adaptations. At the same time, group formation and the learning of social skills were crucial factors in the evolution of human intelligence. This was accompanied by the emergence of language, which expanded the scope of imagination and hence the realms of thought (Draguhn, this volume). In this way, brain and culture co-evolved (Deacon, 2012; Sterelny, 2012; Haidle et al., 2015).

Human intelligence and the emergence of culture are hence associated with the evolution of the brain. Indeed, various cognitive abilities are located in specific parts of the brain. The neocortex is associated with thinking and consciousness. Its volume in humans, especially in the frontoparietal area, is much larger than in primates. To simplify, one could say “that (pre)-frontal parts of the brain are particularly concerned with action, decision-making, and rational impulse control, whereas the parietal cortex integrates multimodal sensory and motor impulses and in this way generates our picture of the current context” (Draguhn, this volume). One could also describe these “association areas,” which are independent of immediate perception and action, as the pinnacle of cognition. Of course, localization theories are always a simplification, and one should not forget that these areas never work on their own but only in dynamic interaction with others, e.g., the thalamus, the basal ganglia, and the limbic system.

Research into the fine-grained structure of neuronal networks reveals various anatomical properties that are important for intelligence. In particular, the number of neurons and synapses are relevant, as is the thickness of the axons. The latter determines the transmission speed of impulses that enable fast and complex information processing. Non-neuronal cells in the brain, called glia cells, also contribute to this. All levels of our neuronal networks are in constant interaction, i.e., the activity of single neurons affects the activity of local networks involved in large-scale activity patterns of the whole brain. Causality is both bottom-up (neurons causing brain-wide activity and behavior) and top-down (behavior and experience entraining the activity of neurons and their synaptic connections). The functions of the brain are reflected in micro- and macro-structures. For example, the folding of the cerebral cortex allows for high local connectivity, which is partly responsible for processing speed and thus for complex thought processes. In line with Fodor (1983), we can say that it is precisely the brain's modular architecture that enables the structural and functional specializations of different areas (Hofman, 2019). Here, clear differences between species become apparent, e.g., Fodor's classical examples of language and (primary) visual processing (cf. Pylyshyn, 1999; Firestone & Scholl, 2016).

As an area of particular importance for "higher" cognitive functions, the human prefrontal cortex is particularly large and rich in cells. It appears to be of key importance for complex thinking and rational decision-making, serving as an organ for "executive control" and "top-down regulation." Similar to all other brain areas, it is not autonomous but is always influenced and regulated by "bottom-up" input from other areas. For the same reason, it is a highly biased, simplified, and anthropocentric view to take the increasing "frontalization" of the brain from "lower" mammals to humans as proof of our rational nature and the superior position of humans in the animal kingdom. The interdependence of the frontal cortex with other brain areas, with the whole organism, and even with the social environment also highlights its ecological dependencies. The brain never works alone but exercises its functions in the context of our experiences and actions as holistic beings. For example, research on neuronal plasticity shows an astonishing, life-long capacity for intellectual development that stems from being embedded in, and interacting with, supportive surroundings (Monyer & Gessmann, 2017).

The findings of neuroscience indicate the conditions conducive to the development of intelligence: secure environmental conditions in conjunction with developmental incentives; early promotion of the ability to think and the capacity to act through learning and practice; repetition (e.g., by memorization) and stimulation of new neural connections (e.g., through musical activity); an appropriate balance between concentration and distraction, focused and associative thinking, and the interplay of coherence and incoherence in neuronal networks (see Holm-Hadulla, 2013).

In short, human intelligence and culture are rooted in our biological make-up, most of all in the structure, functioning, and interactions of the brain. However, it is impossible to reduce the most complex acts of thinking and, even more, the emergence of sophisticated cultural systems such as music, art, philosophy, religion, science, and technology to biological functions only. They emerge at their own levels of complexity, requiring their own, non-biological tools to analyze them and languages to describe them. As a first step in substantiating this conviction, we turn to the psychology of intelligence.

3 The Psychology of Intelligence

Despite increasing insight into the biological and neuroscientific foundations of intelligence, there are still domains of such complexity that they can no longer be explained by physical, chemical, and biological methods—especially in the human sphere. Accordingly, a science has emerged that for over a hundred years has chosen intelligence as one of its central topics: psychology (Funke, this volume).

In 1905, Binet and Simon developed one of the first intelligence tests designed to diagnose and study mental disabilities (see Funke, this volume). In the United States, this test was introduced by Terman as a way of selecting personnel for the intelligent use of complex military technology. At about the same time, Spearman developed a "two-factor theory" that distinguished specific factors of intelligence, such as computational or linguistic ability, from a general intelligence factor. Thurstone (1973), on the other hand, considered this general factor to be a statistical artifact and conceived of intelligent behavior as the interaction between several independent primary abilities: verbal comprehension, word fluency, reasoning, spatial awareness, retentiveness or memory, computational ability or number memory, and perceptual speed or attention (see Funke, this volume). Numerous further developments in the conception and measurement of intelligence followed in the course of the twentieth and twenty-first centuries (see, e.g., Sternberg, 2018). The most common intelligence test today is the Hamburg-Wechsler Intelligence Test (HAWIE, since 2013 WAIS-IV), which is used in different forms for children and adults.

At the theoretical level, Gardner's concept of multiple intelligences is particularly important (1983). According to his research, nine dimensions of intelligence can be distinguished empirically: linguistic, logical–mathematical, musical–rhythmic, pictorial–spatial, bodily–kinesthetic, naturalistic, interpersonal, intrapersonal, and finally existential intelligence (in the sense of wisdom). Especially when it comes to emotional and social intelligence, established measurement methods tend to be overly simplistic compared to the complexity of the functions measured. Funke (this volume) suggests that psychological intelligence research should concern itself less with structures and more with processes, and that more realistic, life-like conditions should be taken account of in tests. These include high complexity, interconnectedness, momentum, obliquity, and multiplicity coupled with a need for multi-dimensional information processing.

Furthermore, Goleman's (2020) notion of emotional intelligence has become widely accepted. It describes the ability to perceive, understand, and influence one's own and others' emotions. One aspect of emotional intelligence is so-called interpersonal intelligence, which already played an important role in Gardner's thinking. Herpertz (this volume) distinguishes a (meta-) cognitive and an emotional component of interpersonal intelligence. The former refers to the ability to adopt other perspectives, i.e., to understand and also anticipate the mental states of others. This reflective perspective is bound up with specific cognitive functions and linguistic expressions and is also referred to as mentalization (Fonagy & Allison, 2012), mind-reading (Goldman, 2006), theory of mind (Premack & Woodruff, 1978), or (cognitive) empathy (Lipps, 1905). The emotional component consists of resonant intuitive empathy based on a kind of direct perception of the way another person's mental life is reflected in his or her expressive behavior (Zahavi, 2014). Neurobiologically, mentalization correlates with activity in cortical midline structures and temporoparietal areas (Herpertz, this volume), whereas resonant intuitive empathy correlates with processes in areas established earlier in our evolution such as the sensorimotor cortex and the anterior insular region. Especially the imitative aspect of affective empathy is closely linked to the so-called mirror neurons (Gallese et al., 1996), i.e., the neuronal substrate that "fires" in a similar way whether a certain action is observed in someone else or carried out by oneself. Mirror neurons have been investigated in great detail by research programs based on a wide range of concepts such as embodied simulation theory (Gallese & Sinigaglia, 2011) or phenomenological anthropology (Breyer, 2015). Ontogenetically, mentalization and empathy are learned through close interaction with early caregivers. Mirror imitation of affective and sensorimotor states can already be observed in the first year of life. It later develops into an intuitive and embodied understanding of the affects and feelings of others (Herpertz, this volume). Processes of joint attention (sharing the focus of attention with others) occur toward the end of the first year of life, and mentalization capacity develops further from there (Tomasello, 2019) (see Fig. 1.1).

Fiedler et al. (this volume) address the question of why human judgment and decision-making so often deviate from the rules of logic. Kahneman and Tversky (1986) have famously highlighted the apparent shortcomings of human intelligence

Fig. 1.1 Mother with child; watercolor by Christel Fahrig-Holm. (Reprinted with permission of the artist)

in countless experiments. However, seemingly irrational behavior can also be adaptive and purposeful, they argue. This perspective has been developed further, reconceiving seemingly faulty heuristics and irrational biases as "fast and frugal" cognitions adapted to particular features of the environment in which decisions are made (Gigerenzer, 2001). We speak of bounded rationality when cognitive capacities are matched to specific environmental demands, as famously illustrated by the availability of recognition heuristics (Todd & Gigenrenzer, 2007).

The flexible transfer of skills to new domains presupposes an ability that Fiedler et al. (this volume) call "metacognition." It monitors, controls, and corrects other cognitive processes. However, deficits in monitoring and controlling one's mental operations are widespread. The authors' term such deficits "metacognitive myopia," which can be a serious obstacle to rational behavior. As examples they refer to uncritical inferencing, counter-productive perseverance, and the disinclination to avoid learning and remembering information known to be false. Awareness of metacognitive myopia is of great practical importance, e.g., in evaluating testimonies and political decisions. Ways of improving metacognitive intelligence include quick and clear feedback, incentives for improvement, and preemptive perpetuation of reliable information. However, metacognitive myopia still remains a major obstacle to rational thought and action. It is puzzling why we often lack the critical judgment required to distinguish false information and obvious fake news from trustworthy sources. The authors advance the interesting hypothesis "that evolution may not have 'forgotten' to strengthen metacognition at all, but may have 'deliberately' suppressed it … The constant attempt to scrutinize and critically test the durability of any information may mean sacrificing a number of other foundations of adaptive intelligence, such as trust in social information, parsimonious heuristics, and rapid automatic priming effects."

4 Mathematical and Artificial Intelligence

The mathematicians Stiehl and Marciniak-Czochra (this volume) define intelligence as a general ability that encompasses reasoning, planning, problem-solving, abstract and complex thinking, and learning from experience. They show that mathematical or algorithmic structures can realize such abilities in an abstract way. For our purposes, this means that there are levels of intelligence that demand to be recognized as such but do not patently depend on biological substrates. This transfer of the concept of intelligence from living beings to ideal, mathematical structures require us to pay close attention to both the transformations that the concept of intelligence undergoes in this process and the degree to which such a transfer is justifiable in the first place.

Above all, mathematical and artificial intelligence play a role in processes that are not readily accessible to intuitive and associative approaches to human intelligence, either because they are too complex, the relevant variables are unknown, or the volume of underlying data exceeds human processing capacity. Mechanistic modeling is an essential element in mathematical intelligence. It is the translation of the items, mechanisms, and processes of a system or issue into formal objects that can be studied using mathematical or computational techniques (Stiehl & Marciniak-Czochra, this volume). Mechanistic modeling can be applied in physics, chemistry, and biology as well as in medicine and economics. It permits the intelligent utilization of complex concepts and even takes account of learning from experience. Of course, mathematical "learning from experience" is not comparable with the way humans incorporate experience into their skills and intelligence. It is best thought of as a stochastic form of adaptation that remains dependent on the intelligence of the mathematicians who pre-define the range and rules of experience-dependent changes. But mechanistic models enable us to predict events, derive conclusions from experience, plan strategies, and solve problems. When they are combined with data-driven techniques such as "machine learning," they help us to model and integrate multiple variables that would otherwise be incomprehensible. It needs to be emphasized that the "meaning" or significance of data only reveals itself through adequate statistical analysis and intelligent interpretation (Weiß, this volume). Data cannot think, nor can they work out solutions independently. Only if we can understand how data are collected, estimate their scope, and establish how they can be used intelligently, can data contribute to the explanation of events and relationships. In the sciences, one of the most important, methodologically sound ways to achieve such intelligent interpretation of data is by the use of models that further the understanding of complex systems and support the generation of hypotheses.

Heuveline and Stiefel (this volume), director of the "Mathematikon" at the University of Heidelberg, argues that artificial intelligence (AI) is first of all a metaphor for decisions driven by algorithms. So-called weak or narrow AI is equivalent to applied mathematics. Weak AI can surpass human intelligence in some areas but is in fact fundamentally different in nature. It encompasses all systems in existence today, for example, those we are familiar with from image and text recognition. So-called strong intelligence, on the other hand, sets out to imitate human intelligence. From a mathematical point of view, there are fundamental reasons why this cannot succeed. Ambitions of this nature will remain science fiction (Heuveline & Stiefel, this volume). There are fundamental differences between mathematical and human intelligence, e.g., concerning the embodied and emotionally resonant understanding of biographically toned moods (see Herpertz, this volume; Fuchs, this volume; Oeming, this volume). This notion, however, does not diminish the importance of AI in specific domains. The benefits of AI in handling the exponentially growing volume of data worldwide are not only striking but also indispensable in this age of "big data."

Because of the importance of AI for society as a whole, Heuveline wants an understanding of algorithms to be integrated into school education. Teachers and pupils need to be informed about the technical potentialities and limitations of AI, as well as the ethical considerations involved and the legal regulations required. One important role of human intelligence in the field of AI is that of safeguarding self-determination and data sovereignty. Further investment in AI is essential, especially in the field of ecological AI or "green IT."

5 Artificial and Human Intelligence

Psychiatrist and philosopher Fuchs (this volume) investigates the fundamental differences between artificial and human intelligence. He proceeds on the assumption that advances in AI and robotics cast increasing doubt on the distinction between simulation and reality. He rejects the idea that social technologies, e.g., as envisioned by the behavioral psychologist Skinner, promise greater happiness for society by means of the technical conditioning of humans. The idea that rational knowledge and corresponding technologies can free humankind from the irrational self-image it is laboring under is also written into plans to increasingly replace human intelligence with AI. According to Fuchs (this volume), the prerequisite for human intelligence is interaction between the living (perceiving and acting) organism and its environment. Human intelligence is fundamentally based on human life. Consequently, it is nonsensical to try to conceive of humanity in terms of information-processing and information-storing strategies gadgets run by electronic algorithms.

If one reduces the human mind and its embodiment in the whole organism to logical operation processes in the brain, analogous to the functioning of computers, serious errors are bound to arise. Most notably such a view is *cerebrocentristic*, i.e., it reduces human intelligence to processes taking place in the brain and consequently cannot adequately account for its grounded nature (Barsalou, 2008). In the light of research on grounding and 4E-cognition (embodied, enacted, extended, embedded), the famous "brain in a vat" appears to be ill-conceived: intelligence presupposes a body in the world (Thompson & Cosmelli, 2011). Furthermore, conceiving of the human mind as analogous to a computer runs the risk of repeating de La Mettrie (1747/1999) notorious "*homme machine*," depriving the human mind of its vitality and its phenomenalistic qualities. On top of that, such a computationalist understanding of the human mind models person-level properties and activities by ascribing the same phenomenological properties (thinking, perceiving, etc.) to subpersonal processes within the brain. The old *homunculus* problem can be descried lurking in the background behind this argument, i.e., we merely transfer the problem to another level, proposing the existence of a "human" or "person" inside our heads. In terms of the language of computationalism, we would do better to conceive of this is as a machine within a machine.

In a similar vein, and harking back to Galileo, Descartes, and Leibniz, Fuchs (2020) criticizes the "idealism of information" that has enjoyed ever greater currency in modern information technology since Alan Turing. Here, thinking is defined as purely connectionist, i.e., in terms of physical processes. It is an approach that encourages the reification of complex life processes and empathic social encounters. Unlike AI, human thinking is inconceivable without inter-corporeal experience. From infancy onwards, the development of human intelligence has to be thought of in terms of "living intersubjectivity." Accordingly, we should never forget that there is a major distinction between scientific intelligence and AI on the one hand and life-world intelligence and embodied social intelligence on the other. In ideal cases, this tension can be productively transformed so that new insights and recommendations for action can be derived from it through dialectical communication (see Holm-Hadulla, 2013, 2020).

AI is increasingly permeating all spheres of science and of social and economic life. Byczkowski and Görtz (this volume) show how AI, especially modern algorithmic approaches, fits in with the basic concepts of observation, experience, cognition, and skill. While not furnishing any complex models for "explaining" the world, the major advances in the field of AI support scientific progress and offer useful practical applications. According to Byczkowski and Goertz, the Industrial Revolution can be divided into four phases: the use of mechanical production equipment, production based on the division of labor, automation of labor, and now the so-called Fourth Industrial Revolution adumbrating fully digitalized and interconnected production. In light of the advances made by AI, it is also possible to conceive of a Fifth Industrial Revolution. Taking medicine as an example, Byczkowski and Görtz (this volume) highlight the opportunities and challenges of AI and intelligent machines. Their conclusion is that AI algorithms will be an integral part of our lives to a larger degree than they already are today. In this context, it is crucial not to think of machines as competitors or enemies, but rather as a potential way of enriching and expanding the horizon of our life-world via technology.

6 Cultural Intelligence

In analogy to "cultural memory" (Assmann, 2011), we speak of "cultural intelligence" when we refer to cultural assets like thinking, judgment, or creativity. Unlike biological intelligence, the cultural variety is embedded in cultural landscapes, architectures, myths, religions, literature, music, visual arts, and other artifacts. Accordingly, it cannot be properly understood using the methods applied by the natural sciences. Cultural intelligence is the expression of a relationship *sui generis* between humankind and the world. In contemporary evolutionary theory, it is commonly accepted that the co-evolution of human nature and human culture has resulted in a unique dynamic through which cultural influences can rapidly exert very strong and lasting effects on human thinking. This encompasses the so-called "ratchet effect," which refers to an accumulation of modifications in our cultural environment that result in an exponential growth process also known as "cumulative culture" (Tennie et al., 2009; Haidle & Schlaudt, 2020). In light of the dynamic nature of cultural intelligence, anthropologists have little choice but to acknowledge that human infants are at least as well adapted to a "symbolic environment" as they are to their natural environment (Tomasello, 2009; Deacon, 2012).

In contemporary cultural studies, culture is understood as "the total complex of ideas, forms of thought, ways of feeling, values, and meanings that materializes in symbol systems" (Nünning & Nünning, 2008, p. 6). Cultural studies will thus necessarily deconstruct traditional certainties. For example, "race," "gender," and "colonization" have become major topics for scholarly reflection and cultural practice.

These examples illustrate the connection between intelligence, wisdom, and ethics. Literature, for example, can expose stereotypes and unjustified hierarchies based on prejudices about the differences between female and male intelligence. Intellectual skills, and especially emotional and social intelligence, can be enhanced by engagement with works of literature. Readers gain insights into cognitive and affective processes that might otherwise have remained a mystery to them. This can lead to changes in attitudes, e.g., about the relationship between instrumental intelligence, wisdom, and ethics. In her discussion of the novels "*Machines Like Me*" by Ian McEwan and "*Klara and the Sun*" by Kazuo Ishiguro, Nünning (this volume) addresses particular problems associated with the decoupling of intelligence, wisdom, and ethics. These texts invite complex reflections on the relationship between analytical and emotional intelligence as well as human and artificial intelligence. They demonstrate that intelligence alone is not sufficient for responsible action. Wisdom and ethics are just as essential (see below).

Cultural intelligence is an aspect of a holistic species of understanding for which we suggest coining the term "life-world intelligence." It is based on everyday experiences in the concrete life-world of individuals and communities very much along the lines of what the ancient Greeks called *phronesis*, i.e., the wisdom of practical life (Aristotle, 2006). Instrumental action, complex thinking, and living intersubjectivity endow us with a feeling of self-efficacy and coherence because they actually help us in coping with the challenges of everyday life (see Holm-Hadulla, 2021). It is a feeling and a conviction that are invariably rooted in a larger cultural whole governed by a different logic than the life-world of individuals.

Scientist, politician, and poet Johann Wolfgang von Goethe is a paradigmatic instance of the importance of cultural intelligence for understanding our life-world and its realities. In his *Faust*, which he worked on over a period of 60 years and has lost none of its relevance to this day, he confronts us with the limits of scientific knowledge: "Have now, alas! studied philosophy/jurisprudence and medicine, /And, alas, also theology/thoroughly, with hot endeavor. /There I stand, poor fool, /And am as wise as before!" (*Faust I*, "Night").

With his poetic resources, Goethe attempts to understand the reality of life and in so doing points up interesting and novel perspectives for the sciences. The topics he enlarges on are astonishingly modern. From an economic perspective, he deals with the risks involved in borrowing without securities, which leads to a "miraculous multiplication of money" (*Faust II*, Act 1, "Large Room"). From an ecological perspective, Goethe's critical appraisal of unchecked expansionism and the ruthless appropriation of land at the cost of human lives, natural resources, and traditional values has gained ever greater relevance (*Faust II*, Act 5, "Open Area"). Even AI and robotics are pre-figured in the *topos* of the creation of the "homunculus" (*Faust II*, Act 2, "Laboratory").

Poetry, art, and music are not merely educative, they also help us to cope with, recognize, and overcome emotional, intellectual, and social conflicts. The arts are essential in transforming hatred and violence (see Holm-Hadulla, 2019). Their cognitive and coping function is still evident today in prominent examples like the painter Gerhard Richter, musicians like Madonna or the Rolling Stones, and poets like Amanda Gorman (2021). Madonna seeks solutions to historical traumas and religious questions and develops considerable social impact by shedding light on social injustices, especially the oppression of women and their sexuality, through provocative depictions that for many are anything but tasteful. In their song "*Sympathy for the Devil*," located somewhere between Bulgakov's *The Master and Margarita* and Goethe's "power which always wills evil and always creates good," the Rolling Stones address historical atrocities. Their song describes various forms of human destructiveness. It covers topics such as the crucifixion of Jesus Christ, the murder of the Tsar's family after the Soviet October Revolution, the Hundred Years War between England and France, the ritual murder of troubadours in India, and the assassinations of the Kennedy brothers. The essential message is that evil must be faced if it is to be overcome (Holm-Hadulla, 2019).

Goethe speaks of the healing potential of artistic and musical intelligence: "Sad is our mind, confused are our endeavors; /how the lofty world fades away from our senses!/And then music hovers by on its angel's wings, /interweaving one tone with another into millions, /in order to penetrate man's being through and through, to fill him over-abundantly with eternal beauty …" (Appelbaum, 1999, p. 206).

Thus, music can be seen as a spiritual refuge where we learn that the experience of beauty is vital for a good life. Reflection on the cognitive foundations of beauty has a long-standing tradition in our culture, going back at least to Plato, and would require a separate treatise. Of course, this is not restricted to music but also applies to the visual arts. Gerhard Richter, for example, explores his personal biography by engaging with contemporary history in his paintings. Encounters with art can bestow flashes of insight that cannot properly be grasped scientifically. Shakespeare sums this up in a way that remains fully valid to this day: "Such shaping fantasies, that apprehend/More than cool reason ever comprehends." (Shakespeare, *A Midsummer Night's Dream*, Act 5, Scene 1).

Just like scientific knowledge, cultural and artistic knowledge needs to establish a connection with practical life if it is to serve as an ethical guide for human action. History is rife with art that has been exploited to spread hate and violence instead of trusting to its poetic transformation of the world. Richard Wagner's mythical motifs are an extreme example of this. They were appropriated by Adolf Hitler and his henchmen for a politics of immorality that considered itself "artistic" (Fest, 2002). Nevertheless, artistic intelligence remains essential for the creative transformation of destructiveness. We see this in the transformative intelligence informing the composition of Botticelli's *Birth of Venus*. The painting shows how Aphrodite—the equivalent of the Roman Venus—is born from the foam of the waves and carried ashore by a shell (see Fig. 1.2). In the myth, however, Aphrodite, the goddess of beauty and fertility, has much more sinister origins. Part of Botticelli's accomplishment resides precisely in transforming the archaic violence of the myth into the beauty of his painting (see Holm-Hadulla, 2011).

Beginning with the earliest cultural artifacts, humans have engaged in communication about themselves and their environment by means of animistic and metaphysical ideas later elaborated in the form of complex myths. Religions and philosophies developed these ideas further, ideas deriving from the natural world

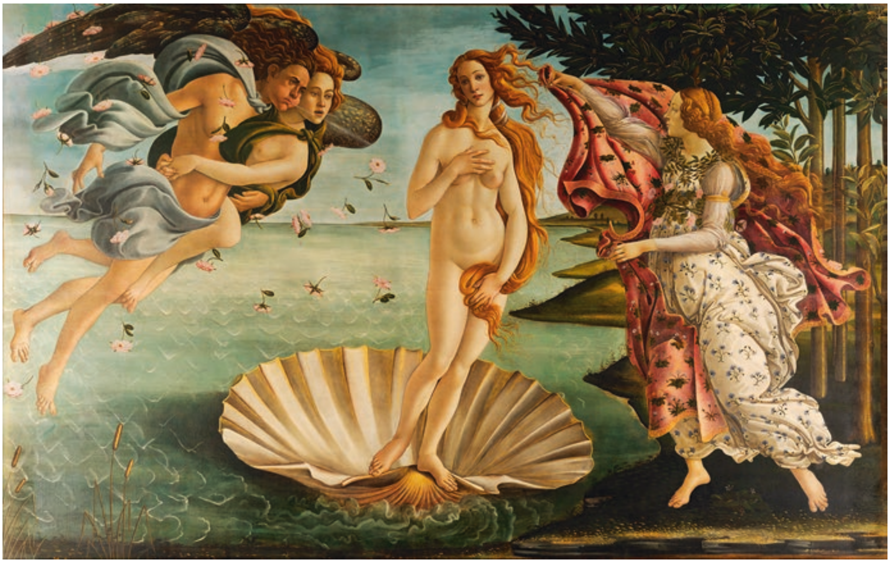

Fig. 1.2 "Birth of Venus" by Sandro Botticelli (created c. 1484–1486). (Source: https://de.wikipedia.org/wiki/Die_Geburt_der_Venus_(Botticelli))

and designed to provide guidance for a good life and for meaningful communal organization. Linguistic and esthetic forms are essential here because they perpetuate the contents of cultural memory in ways completely beyond the reach of the animal kingdom. Not only since the "Axial Age" around 500 BC (Jaspers, 1949), in which new interpretations of man, the world, and personal and political life emerged simultaneously in the most diverse regions of the world, has it been legitimate to speak of specifically human intelligence. The thinkers of the Axial Age—Confucius and Lao-tzu, Gautama Buddha, Zarathustra, the Old Testament prophets, the pre-Socratic philosophers, etc.—show very clearly how far human intelligence had emancipated itself from its natural conditions. With the mediation of thinkers such as Plato and Aristotle, they continue to shape the world of our imagination to this day.

7 Political Intelligence and Wisdom

In fine, the highest form of intelligence is neither technological nor artistic, but ethical and political. This idea can be traced back to ancient Greece and ancient China, e.g., in the writings of Plato, 428/427-348/347 and Confucius, 551-479. The very same idea lies at the root of the democratic discourse ethic (see above; cf. Habermas, 2011).

The psychologist Sternberg argues that meta-theoretically individual forms of intelligence—analytic, fluid, or crystalline—can be incorporated into the value-based concept of "wisdom" (Sternberg, 2003). He suggests that the same "meta-components" underlie these different aspects of intelligence, identifying a problem, defining its nature, formulating strategies for solving it, and so forth. In the field of formal intelligence, these components figure in the acquisition, application, and analysis of knowledge, whereas in creative intelligence they are associated more with finding new and useful ideas. Wisdom, on the other hand, is concerned more with "common goods" (Sternberg, this volume). To better understand the interplay, i.e., the dependencies and independencies of the different levels of intelligence described so far, Sternberg proposes a new construct—that of "meta-intelligence." In so doing, he lays bare the problem that intelligence can be used for (self-)destruction. Accordingly, the factors constitutive for intelligence need to be supplemented by an adaptive intelligence factor—that of wisdom.

Yet it still remains questionable whether the phenomena of intelligence and wisdom can be captured via the methods of empirical psychology. Psychological research is already extended to its limits when it comes to evaluating creative products. It cannot adequately capture such things as the originality and benefit of, say, a mathematical proof, a scientific discovery, a poem, or a song. The psychology of creativity is dependent on evaluation criteria that are drawn from the life-world of the individual or from the various scientific disciplines (cf. Funke, 2009). Even in the case of wisdom, psychology is operating in a realm that cannot be adequately grasped without recourse to historical, philosophical, and political theories on the one hand, and practical and embodied experiences from the life-world on the other. This is why building bridges between these sciences is so essential. Addressing the global challenges we are facing today, such as climate change, water and air pollution, weapons of mass destruction, and the present pandemic, requires an interdisciplinary discourse ethic (Habermas, 2011). This ethic presupposes a form of moral intelligence that is associated more often than not with religious wisdom.

Theologist Oeming makes the case for this view in his article on "*Intelligentia Dei*" (this volume). He argues that many of our modern conceptions of AI and human intelligence are indebted to religious terminology. That implies that these conceptions are embedded in transcendent wisdom deriving from ancient biblical traditions. In the same vein one could also speak of "divine intelligence." This form of intelligence functions in a similar way to one of Kant's regulative ideas in that it confronts human self-overestimation, which is oblivious of its limits, with the ideal of infinity: "It proves to be a necessary corrective against an absurd, totally illusory and self-overestimating belief in technology" (Oeming, this volume).

Religious language also permeates modern natural science. It is, for example, used in the absurd attempts to sacralize AI, as exemplified by the plans to "program God." AI is presented as the business model that will save the world. All this is devoid of wisdom and cultural memory and hence devoid of the essential features that make us human. As a remedy, many intelligent ideas can be found in biblical texts that further our self-understanding and promote meaningful social coexistence. In ancient Greek philosophy, there are noteworthy analogies to biblical texts on the limitations of human knowledge. Oeming (this volume) demonstrates—in Plato's (1985) *Politeia*—how the distinction between appearance and reality is furthered through engagement with mythical ideas. However, the Bible encourages skepticism with regard to the Socratic hope that humankind can be guided to the true, the good, and the beautiful through philosophical education.

On the one hand, the Bible is science-friendly: "Subjugate the earth!" This imperative is readily interpreted as encompassing the exploitation of all the technical resources at our command. But we should be wary of such interpretations. Man must not become a technological Proteus. On the contrary, as humans we must come to terms with our often fractured selves. For Oeming, faith and the critical thinking of the enlightenment belong together. Thus, religious wisdom remains open to technicians and scientists. Albert Einstein expressed this as follows:

"To feel that behind what can be experienced there is hidden something inaccessible to our mind whose beauty and sublimity reach us only mediately and in faint reflection, that is religiosity" (cited after Oeming, this volume). Belief in a form of wisdom that precedes and transcends us is not only religious but also and at the same time philosophical and political.

However, there exists a remarkable contrast between the philosophical idealization of politics and the poor repute in which it stands. One reason for this may be the complexity of political decision-making and the high pace at which opinions have to be formed. In politics, people are constantly "driven by short-term pressure to react immediately and to have a well-founded opinion on everything and everyone" (Bauer, this volume). Politics constantly has to balance different and sometimes conflicting perspectives and interests, organize majorities, and negotiate compromises. Thus, politics is regarded by many as a "dirty business." However, the viability of liberal democracy hinges on the fact that the quest for what is good, true, and beautiful must always stay in touch with the processes of public discourse: "Political intelligence thrives on preconditions that politicians cannot create on their own. It lives from the power of judgment, the sense of responsibility, and the ability of many to face the tasks of the present and the future. Good persuasion, feasible approaches to solutions, persistent securing of majorities and resources is at the core of our business as politicians—and it undoubtedly requires some political intelligence to do so" (Bauer, this volume).

Political intelligence combines both a moral and a practical worldview. As such, it transcends instrumental and operational intelligence and is in some respects closer to wisdom. Harnisch (this volume) illustrates the tension between political intelligence and wisdom by contrasting Aristotle's morality-oriented prudence with Machiavelli's utility-oriented astuteness. Political wisdom is a relational concept that combines cognitive and affective self-orientation processes with the ability to understand others as part of a political community (Harnisch, this volume). Such wisdom must deal with considerable complexity in pluralistic societies and be sufficiently flexible to find adequate solutions for the rival claims of knowledge and interest. In other words, it functions in the same way as Aristotle's *phronesis*, which transcends mere knowing (*episteme*) and doing (*poiesis*).

Thus, it behooves political wisdom to integrate findings from different perspectives, including individual scientific disciplines, within the horizon of the life-world. This function of mediating between the parts and the whole is essential to political wisdom and links it to the tradition of hermeneutic understanding (Gadamer, 2008). It acknowledges that any interpretation will rest on a prior understanding of the phenomena involved and proceeds by breaking down and revising such preconceptions in the light of what is learned in the course of interpretation. This structure is the reason why we speak of a hermeneutic circle. It also encompasses another aspect, namely that scientific knowledge is historically and socially contextualized. In order to understand a given scientific insight, hermeneutical understanding considers aspects such as the discursive structure it is relevant to, the scientific works it builds on, the politics of its time, and so forth. Lastly, hermeneutics is akin to Socratic dialectics in stressing that truth is the result of a shared process of understanding. Hence, hermeneutical understanding entails an interactionalist or dialogical conception of truth. It is hard to explain this interactionalist and communicative dimension of intelligence with the methods of the empirical sciences. Its clearest expression can be found in the socio-political struggle for recognition (Hegel, 1807/2007; Habermas, 2011; Honneth, 2014). In a similar vein, Goethe formulates a relevant imperative at around the same time as the aphorism on nature quoted at the beginning of this article: "Let man be noble, /helpful and kind!/For that alone/distinguishes him/from all other beings/that we know … /For nature/is unfeeling/the sun shines/for evil and good men alike, /and the moon and the stars beam/for the criminal/as for the best of men." (Appelbaum, 1999, p. 73).

Today, we have a more ambivalent attitude to the idea of moral superiority, and we are no longer so quick to place human intelligence above everything else. Nevertheless, nature itself is blind to its destructive forces, so that all hope for a better future resides in humanity. We humans must use our multiple intelligences responsibly, not only for our own benefit but also for the protection of nature as a whole. To this end, the individual scientific disciplines are helpful. But how their findings results and methods can best be communicated on the interdisciplinary plane remains an open question. As far as we know, Hegel was one of the last to try to fit the individual sciences into a hierarchical system (1817/1991). To be relevant for today's sciences, such systems require thorough revision. Nonetheless, in our bid to understand ourselves and the world around us, we are in dire need of the holistic view. Both philosophers like Richard Rorty (2000) and neuroscientists like Singer (1990) emphasize the need for a perpetual effort to create such forms of understanding (see Holm-Hadulla, 2013).

Ultimately, political intelligence and wisdom are necessary to mediate between, and communicate with, the individual scientific disciplines, especially with regard to their real-world applications. Many aspects of science and the life-world demand to be taken into account when dealing with major issues such as climate and peace policy. One topical example of this need for mediation between science and life-world experiences is the ongoing fight against the Covid-19 pandemic. Epidemiologic and virological knowledge alone cannot justify the restrictions on social contacts. Instead, the respective policy-makers must bear in mind a multiplicity of medical issues (e.g., delays in the treatment of heart attacks), neurological consequences (e.g., delays in treatment for strokes), and oncological problems (postponed surgery), before sensible policy decisions be made. In addition, they need to train their sights on the psychological, social, economic, cultural, legal, and societal consequences. Wise policies will take account of individual life-world experiences as well. Seen thus, policy-making is the impossible art of the possible.

Of course, it is virtually impossible for politicians to validate the findings of individual scientific disciplines and integrate them into an overall plan of action. This would require politicians to exhibit a form of wisdom enabling them to conceive of the plurality of scientific contributions in the light of a pre-existing holistic concept. Such holistic concepts were once provided by religions and traditional teachings of wisdom but have lost their binding force in liberal democracies. On the other hand, philosophical thinking oriented toward the whole is not only present in the sciences but is an integral part of everyday life and finds expression in the subliminal striving for a coherent worldview and a concept of meaningful action. This form of intelligence is characterized "by its reference to the world as a whole, that is, to what we know of the world at a given historical point in time, as well as by the systematic self-reference of researchers to themselves as human beings, both as individuals and as persons in general, and then to themselves as members of a social community" (Habermas, 2019, p. 27f). Philosophical intelligence understood in this way we refer to as wisdom, and it encompasses life-world experiences and cultural thought patterns alike. Individual understanding and political understanding emerge in democratic societies "within the framework of a generalized and reasonable, critically examined and rationally elaborated prior understanding that contemporaries have of the world, albeit at different levels of mental articulation, as reflected in their lifeworld" (op. cit., p. 28). In this respect, intelligent policies are wise integrations of multidisciplinary perspectives and their practical applications.

References

Albertin, C. B., Simakov, O., Mitros, T., Wang, Z. Y., Pungor, J. R., Edsinger-Gonzales, E., Brenner, S., Ragsdale, C. W., & Rokhsar, D. S. (2015). The octopus genome and the evolution of cephalopod neural and morphological novelties. *Nature, 524*(7564), 220–224.

Appelbaum, S. (1999). *103 Great poems by Johann Wolfgang von Goethe*. Dover Publications.

Aristotle. (2006). *Nicomachean ethics*. Rowohlt.

Assmann, J. (2011). Cultural memory and early civilization: Writing, remembrance, and political imagination. Cambridge University Press.

Barsalou, L. W. (2008). Grounded cognition. *Annual Review of Psychology, 59*, 617–645.

Bauer, T. (this volume). Political intelligence? A view from practice between politics and science. In R. M. Holm-Hadulla, J. Funke, & M. Wink (Eds.), *Intelligence – Theoretical foundations and practical applications*. Heidelberg University Press.

Breyer, T. (2015). *Verkörperte Intersubjektivität und Empathie. Philosophisch-anthropologische Untersuchungen Vittorio Klostermann*. Vittorio Klostermann.

Byczkowski, M., & Görtz, M. (this volume). The industrialization of intelligence. In R. M. Holm-Hadulla, J. Funke, & M. Wink (Eds.), *Intelligence – Theoretical foundations and practical applications*. Heidelberg University Press.

Darwin, C. (1859). *On the origin of species by means of natural selection, or the preservation of favoured races in the struggle for life*. J. Murray.

Deacon, T. W. (2012). Beyond the symbolic species. In T. Schilhab, F. Stjernfelt, & T. Deacon (Eds.), *The symbolic species evolved. Biosemiotics* (Vol. 6). Springer.

Dicke, U., & Roth, G. (2016). Neuronal factors determining high intelligence. *Philosophical Transactions of the Royal Society, B: Biological Sciences, 371*(1685), 20150180.

Draguhn, A. (this volume). Neurobiology of intelligence. In R. M. Holm-Hadulla, J. Funke, & M. Wink (Eds.), *Intelligence – Theoretical foundations and practical applications*. Heidelberg University Press.

Erbar, C., & Leins, P. (this volume). The intelligent play with coincidences and selection. In R. M. Holm-Hadulla, J. Funke, & M. Wink (Eds.), *Intelligence – Theoretical foundations and practical applications*. Heidelberg University Press.

Fest, J. (2002). *Hitler*. Harcourt.

Fiedler, K., Florian, E., & Salmen, K. (this volume). Metacognitive myopia – Obstacle to intelligent behavior and failure of evolution? In R. M. Holm-Hadulla, J. Funke, & M. Wink (Eds.), *Intelligence – Theoretical foundations and practical applications*. Heidelberg University Press.

Firestone, C., & Scholl, B. J. (2016). Cognition does not affect perception: Evaluating the evidence for "top-down" effects. *Behavioral and Brain Sciences, 39*, 1–77.

Fodor, J. A. (1983). *The modularity of mind*. The MIT Press.

Fonagy, P., & Allison, E. (2012). What is mentalization? The concept and its foundations in developmental research. Minding the child: Mentalization-based interventions with children, young people and their families, 11–34.

Fuchs, T. (2020). *Verteidigung des Menschen. Grundfragen einer verkörperten Anthropologie*. Suhrkamp.

Fuchs, T. (this volume). Human and artificial intelligence - A critical comparison. In R. M. Holm-Hadulla, J. Funke, & M. Wink (Eds.), *Intelligence – Theoretical foundations and practical applications*. Heidelberg University Press.

Funke, J. (2009). On the psychology of creativity. In P. Meusburger, J. Funke, & E. Wunder (Eds.), *Milieus of creativity*. Springer.

Funke, J. (this volume). Intelligence: The psychological view. In R. M. Holm-Hadulla, J. Funke, & M. Wink (Eds.), *Intelligence – Theoretical foundations and practical applications*. Heidelberg University Press.

Gadamer, H. G. (2008). *Philosophical hermeneutics*. University of California Press.

Gallese, V., & Sinigaglia, C. (2011). What is so special about embodied simulation? *Trends in Cognitive Sciences, 15*(11), 512–519.

Gallese, V., Fadiga, L., Fogassi, L., & Rizzolatti, G. (1996). Action recognition in the premotor cortex. *Brain, 119*(2), 593–609.

Gardner, H. (1983). *The theory of multiple intelligences*. Heinemann.

Gigerenzer, G. (2001). The Adaptive Toolbox: Toward Rationality. *Evolutionary psychology and motivation, 48*, 113–143

Godfrey-Smith, P. (2016). *Other minds: The octopus, the sea, and the deep origins of consciousness*. Farrar, Straus and Giroux.

Goethe, J. W. v. (1981). *Gesammelte Werke. Hamburger Ausgabe*. C.H. Beck.

Goldman, A. I. (2006). *Simulating minds: The philosophy, psychology, and neuroscience of mindreading*. Oxford University Press.

Goleman, D. (2020). *Emotional intelligence*. Bloomsbury.

Gorman, A. (2021). *The hill we climb: An inaugural poem for the country*. Hoffmann und Campe.

Habermas, J. (2011). *The discourse theory of law and democracy*. Stanford University Press.

Habermas, J. (2019). *Auch eine Geschichte der Philosophie* (Vol. 1). Suhrkamp.

Haidle, M. N., & Schlaudt, O. (2020). Where does cumulative culture begin? A plea for a sociologically informed perspective. *Biological Theory, 15*, 161–174.

Haidle, M. N., Bolus, M., Collard, M., Conard, N. J., Garofoli, D., Lombard, M., Nowell, A., Tennie, C., & Whiten, A. (2015). The nature of culture: An eight-grade model for the evolution and expansion of cultural capacities in hominins and other animals. *Journal of Anthropological Sciences, 93*, 43–70.

Harnisch, S. (this volume). Political intelligence and wisdom. In R. M. Holm-Hadulla, J. Funke, & M. Wink (Eds.), *Intelligence – Theoretical foundations and practical applications*. Heidelberg University Press.

Hegel, G. W. F. (1807/2007). *Phenomenology of spirit*. Duke University Press.

Hegel, G. W. F. (1817/1991). *Enzyklopädie der philosophischen Wissenschaften im Grundrisse*. Meiner.

Herpertz, S. (this volume). Interpersonal intelligence. In R. M. Holm-Hadulla, J. Funke, & M. Wink (Eds.), *Intelligence – Theoretical foundations and practical applications*. Heidelberg University Press.

Heuveline, V., & Stiefel, V. (this volume). Artificial intelligence and algorithms - True progress or just digital alchemy? In R. M. Holm-Hadulla, J. Funke, & M. Wink (Eds.), *Intelligence – Theoretical foundations and practical applications*. Heidelberg University Press.

Hofman, M. A. (2019). On the nature and evolution of the human mind. *Progress in Brain Research, 250*, 251–283.

Holm-Hadulla, R. M. (2011). *Kreativität zwischen Schöpfung und Zerstörung*. Vandenhoeck & Ruprecht.

Holm-Hadulla, R. M. (2013). The dialectic of Creativity: Towards an integration of neurobiological, psychological, socio-cultural and practical aspects of the creative process. *Creativity Research Journal, 25*(3), 1–7.

Holm-Hadulla, R. M. (2019). Sympathy for the devil – The creative transformation of the evil. *Journal of Genius and Eminence, 5*(1), 1–11.

Holm-Hadulla, R. M. (2020). Creativity and positive psychology in psychotherapy. *International Review of Psychiatry, 32*(7–8), 616–624.

Holm-Hadulla, R. M. (2021). *Integrative psychotherapie. Ein schulenübergreifendes Modell anhand von exemplarischen Geschichten aus der Praxis* [The recovered voice – Tales of practical psychotherapy]. Psychosozial.

Holstein, T. (this volume). Intelligence: Evolutionary biological foundations and perspectives. In R. M. Holm-Hadulla, J. Funke, & M. Wink (Eds.), *Intelligence – Theoretical foundations and practical applications*. Heidelberg University Press.

Honneth, A. (2014). *Kampf um Anerkennung. Zur moralischen Grammatik sozialer Konflikte*. Suhrkamp.

Huxley, T. H. (1869). Nature: Aphorisms by Goethe. *Nature, 1*(1), 9–11.

Jaspers, K. (1949). *Vom Ursprung und Ziel der Geschichte*. Piper.

Kandel, E. R., Schwartz, J. H., Jessell, T. M., Siegelbaum, S., Hudspeth, A. J., & Mack, S. (Eds.). (2000). *Principles of neural science*. McGraw-Hill.

Kahneman, D., & Tversky, A. (1986). Rational choice and the framing of decisions. *Journal of business, 59*(4), 251–278.

de La Mettrie, J. O. (1747/1999). *L'homme machine*. Denoël.

Lipps, T. (1905). Das Wissen vom fremden Ich. In T. Lipps (Ed.), *Psychologische Untersuchungen*. Wilhelm Engelmann.

Mao, Y., Catacchio, C. R., Hillier, L. W., Porubsky, D., Li, R., Sulovari, A., Fernandes, J. D., Montinaro, F., Gordon, D. S., Storer, J. M., Haukness, M., Fiddes, I. T., Murali, S. C., Dishuck, P. C., Hsieh, P., Harvey, W. T., Audano, P. A., Mercuri, L., Piccolo, I., … Eichler, E. E. (2021). A high-quality bonobo genome refines the analysis of hominid evolution. *Nature, 594*(7861), 77–81.

Mitchell, S. D. (1987). Competing units of selection?: A case of symbiosis. *Philosophy of Science, 54*(3), 351–367.

Monyer, H., & Gessmann, M. (2017). *Das geniale Gedächtnis: Wie das Gehirn aus der Vergangenheit unsere Zukunft macht*. Albrecht Knaus Verlag.

Nieder, A., Wagener, L., & Rinnert, P. (2020). A neural correlate of sensory consciousness in a corvid bird. *Science, 369*(6511), 1626–1629.

Nünning, V. (this volume). Intelligence in and with Literature. In R. M. Holm-Hadulla, J. Funke, & M. Wink (Eds.), *Intelligence – Theoretical foundations and practical applications*. Heidelberg University Press.

Nünning, V., & Nünning, A. (2008). Kulturwissenschaften: Eine multiperspektivische Einführung in einen interdisziplinären Diskussionszusammenhang. In A. Nünning & V. Nünning (Eds.), *Einführung in die Kulturwissenschaften. Theoretische Grundlagen – Ansätze – Perspektiven*. Springer.

Oeming, M. (this volume). Intelligentia Dei - Artificial intelligence, human reason and divine wisdom. In R. M. Holm-Hadulla, J. Funke, & M. Wink (Eds.), *Intelligence – Theoretical foundations and practical applications*. Heidelberg University Press.

Plato. (1985). *Der Staat (Politeia)*. Reclam.

Premack, D., & Woodruff, G. (1978). Does the chimpanzee have a theory of mind? *Behavioral and Brain Sciences, 1*(4), 515–526.

Pylyshyn, Z. (1999). Is vision continuous with cognition? The case for cognitive impenetrability of visual perception. *Behavioral and Brain Sciences, 22*(3), 341–365.

Rorty, R. (2000). Universality and Truth. In R. B. Brandom (Ed.), *Rorty and his Critics*. Blackwell.

Schnell, A. K., Boeckle, M., Rivera, M., Clayton, N. S., & Hanlon, R. T. (2021). Cuttlefish exert self-control in a delay of gratification task. *Proceedings of the Royal Society B, 288*(1946), 20203161.

Shakespeare, W. (1951). *Complete works*. Harper Collins.

Singer, W. (1990). Search for coherence: A basic principle of cortical self-organization. *Concept in Neuroscience, 1*, 1–26.

Sterelny, K. (2012). *The evolved apprentice. How evolution made humans unique*. The MIT Press.

Sternberg, R. J. (2003). *Wisdom, intelligence, and creativity synthesized*. Cambridge University Press.

Sternberg, R. J. (2018). Theories of intelligence. In S. I. Pfeiffer, E. Shaunessy-Dedrick, & M. Foley-Nicpon (Eds.), APA handbook of giftedness and talent (pp. 145–161). American Psychological Association. https://doi.org/10.1037/0000038-010

Sternberg, R. (this volume). Meta-intelligence: Understanding control, and coordination of higher cognitive processes. In R. M. Holm-Hadulla, J. Funke, & M. Wink (Eds.), *Intelligence – Theoretical foundations and practical applications*. Heidelberg University Press.

Stiehl, T., & Marciniak-Czochra, A. (this volume). Intelligent algorithms and equations? - An approach to the intelligence of mathematical concepts. In R. M. Holm-Hadulla, J. Funke, & M. Wink (Eds.), *Intelligence – Theoretical foundations and practical applications*. Society of Friends of Heidelberg University e.V.

Tennie, C., Call, J., & Tomasello, M. (2009). Ratcheting up the ratchet: On the evolution of cumulative culture. *Philosophical Transactions of the Royal Society, B: Biological Sciences, 364*(1528), 2405–2415.

Thompson, E., & Cosmelli, D. (2011). Brain in a vat or body in a world? Brainbound versus enactive views of experience. *Philosophical Topics, 39*, 163–180.

Thurstone, L. L. (1973). Primary mental abilities. In The measurement of intelligence (pp. 131–136). Springer,

Todd, P. M., & Gigerenzer, G. (2007). Environments that make us smart: Ecological rationality. *Current directions in psychological science, 16*(3), 167–171.

Tomasello, M. (2009). *The cultural origins of human cognition*. Harvard University Press.

Tomasello, M. (2019). Becoming Human: A Theory of Ontogeny. Cambridge, MA and London, England: Harvard University Press. https://doi.org/10.4159/9780674988651

Weiß, C. (this volume). Intelligent algorithms and equations? – An approach to the intelligence of mathematical concepts. In R. M. Holm-Hadulla, J. Funke, & M. Wink (Eds.), *Intelligence – Theoretical foundations and practical applications*. Heidelberg University Press.

Wink, M. (this volume). Intelligence in animals. In R. M. Holm-Hadulla, J. Funke, & M. Wink (Eds.), *Intelligence – Theoretical foundations and practical applications*. Heidelberg University Press.

Zahavi, D. (2014). Self and other: Exploring Subjectivity, Empathy, and Shame. Oxford University Press: Oxford.

Rainer M. Holm-Hadulla pursued a career as a psychiatrist, psychotherapist, and psychoanalyst, after studying medicine and philosophy. His clinical work continues to this day and also his teaching and research at the University of Heidelberg and various other universities, especially in South America. Because of his contribution to creativity research he has been appointed to national and international Centers for Advanced Studies. His most important books in English language are: "Goethe's Path to Creativity"; "The Recovered Voice – Tales of Practical Psychotherapy"; "The Art of Counseling and Psychotherapy."

Hannes Wendler is a Mercator Fellow at the a.r.t.e.s. Graduate School for the Humanities at the university of Cologne and collaborates with Heidelberg's university clinic. You can find his podcast on philosophy and psychology online: https://www.phi-psy.de/fipsi-der-philosophisch-psychologische-podcast/. His publications in English language include "Philosophical Primatology: Reflections on Theses of Anthropological Difference, the Logic of Anthropomorphism and Anthropodenial, and the Self-other Category Mistake Within the Scope of Cognitive Primate Research" *Biological Theory* 2019, and a forthcoming article "The Apology of Hatred: A Positive Phenomenology of Disvalue-Discovery" (together with Alexander Wendt). The Review for Philosophy and Psychology – Special Issue: Hostile Emotions. Springer.

Part I
Biological Basics

Chapter 2
On the Neurobiology of Intelligence

Andreas Draguhn

Abstract Intelligence, defined as the capacity to solve problems through cognition, is strongly related to the brain and its functions. Neuroscience can therefore help to elucidate its natural history, biological constraints, and the causal mechanisms leading to the emergence of intelligence. Indeed, comparative approaches between species have identified brain regions and network properties of particular importance. Within the human species, several structural and functional determinants of intelligence have been identified. This pertains also to the "nature–nurture" problem, i.e., how far intelligence can be influenced by external factors. Our understanding of biological mechanisms and constraints is far from complete, but clearly indicates that favorable conditions are necessary and efficient to help people develop their full potential. Converging with other sciences and social practices neurobiological results indicate that intellectual development should be supported as early as possible, including a rich environment, variable cues and challenges, and reliable, close human relationships.

1 Introduction

Many of us may have observed slipper animals (paramecium) when we made our first experience with a microscope. It is obvious that this simple, single-celled organism behaves actively. It reverses its swimming direction when it encounters an obstacle, and it reacts to chemical and thermal stimuli such that it moves toward supportive environments and avoids dangers. With such skills, these simple organisms manage to survive in a wide variety of habitats—from the sea to fresh water to the rumen of sheep. Does this adaptive capacity justify calling them "intelligent"?

A. Draguhn (✉)
Institute for Physiology and Pathophysiology, Medical Faculty, University of Heidelberg, Heidelberg, Germany
e-mail: andreas.draguhn@physiologie.uni-heidelberg.de; http://www.medizinische-fakultaet-hd.uni-heidelberg.de/Draguhn-Andreas-Prof-Dr.110991.0.html

R. M. Holm-Hadulla et al. (eds.), *Intelligence - Theories and Applications*,
https://doi.org/10.1007/978-3-031-04198-3_2

Or does intelligence only exist in “higher” animals? Perhaps even only in humans? Do we find it in computers or robots? Is our intelligence fully inherited or can we increase it through learning and experience?

We may all have asked ourselves these or similar questions, because they affect our self-image and probably our self-esteem. They are also of great importance for society, particularly in form of the “nature–nurture” debate about innate or acquired intelligence, which has immediate implications for decisions in the realm of education and social politics. In addition, our cognitive abilities are often treated as a genuine value that contributes to our dignity and justifies our supposed superiority over other creatures (or, in unlucky cases, our inferiority). This may be explicitly alleged and defended, as in the utilitarian philosophy of Singer (2013), or it may be inferred implicitly, as in the everyday devaluation of fellow humans with apparently lower intellectual abilities than ours. Ultimately, the creationist idea of “intelligent design” uses intelligence as a name-giving feature of the creator. On the other side, current debates tend to extend the attribute of intelligence to non-humans, including animals, computers, robots and, most recently, even plants (Brenner et al., 2006; Trewavas, 2016). All these discourses make use of ideas or facts about the material basis for intelligence. That is why it is justified and important to study the physical conditions and constraints of intelligence.

Research on intelligence builds on a long history, and modern theoretical frameworks have been largely developed within various branches of psychology. The definitions of the term “intelligence” are complex, especially because intelligence cannot be directly observed. It is, rather, a theoretical construct and a latent variable that has to be indirectly inferred from measurable variables (e.g., the performance in an intelligence test). In this article, we will use a pragmatic definition of intelligence which captures the prevailing concept both in scientific and common language: **Intelligence is the ability to solve problems by flexible cognition and behavior**. In this context, cognition and behavior emphasize the intentional nature of problem-solving, i.e., they go beyond purely reflexive automatisms. In other words, intelligence implies **agency**. With this definition, a mental dimension is addressed, albeit in a broad and action-oriented sense. Intelligence is, hence, a property of living beings (or perhaps machines) that encounter problems and can actively control their behavior. The existence of “problems” implies that the carrier of intelligence has inherent interests, such that, for example, it appears relevant whether it is being eaten or not. Problem-solving by “cognition” and “behavior” implies that there is choice, which requires an inner “space” in which various options can be represented, compared and evaluated without being identical with external actions. The slipper animal is thus ruled out—at least we have no indication that it is able to consider different swimming directions before deciding whether it will navigate backward, left or right. Most scientists assume that intelligence is linked to a system allowing integration and processing of information, decision-making, and initiating an appropriate action. Usually, this central system is a brain. Various authors also name specific properties of brains that enable intelligence, such as a short-term memory in which relevant contexts can be kept present during information processing and decision-making. With this, we assume that the capacity for cognition which is detached from immediate action is a minimal requirement for intelligence. We explicitly do not consider concepts of consciousness in this context, although some texts treat intelligence and consciousness almost synonymously, often with a hierarchical designation of both attributes to "higher" animals and humans. In any case, this notion would need an independent justification (and might turn out wrong). Here, we focus exclusively on intelligence per se, and consider its neurobiological correlates.

2 The Neurobiology of Intelligence

2.1 Are Plants Intelligent?

As a starting point, we will take up the above-mentioned recent postulate that plants are intelligent. At first sight, it seems obvious that humans do, and plants do not possess intelligence, because we have a brain and are able to think while there is no evidence for cognition or behavioral choice in the latter. We would rather think that plant "behavior" is simply based on reactions to physical stimuli (light, water, temperature, touch, etc.), according to predetermined mechanisms. However, not everybody agrees with this apparently trivial notion. Some botanists or plant scientists claim that plants do indeed express sentience, cognition, intelligence, and even consciousness. Publications from this recently developing branch of science range from articles in established scientific journals to popular books attributing human-like behaviors and experience to plants (e.g. Brenner et al., 2006; Trewavas, 2016; Wohlleben, 2015, 2016). "*Plant Neurobiology*" has become a small discipline in its own right. The core of the argument is that plants not only respond locally to environmental stimuli, but also transmit electrical or hormonal signals throughout their body, integrate them in specialized tissues, and then show adapted, systemic responses. The place for this integrative function is sometimes located in the root, sometimes in a conductive, widely distributed tissue called the meristem. None of these, however, fulfills any of the characteristic functions of central nervous systems which would enable plants to feel, think, and act following own intentions (Robinsin & Draguhn, 2021). One research group has even found evidence of associative learning in plants and cites these experiments as evidence for plant consciousness (Gagliano et al., 2016). However, these results have not yet been reproduced, and associative learning is not an established criterion for consciousness. In summary, the claim of intelligent behavior in plants is not backed by any scientific evidence for mental processes in the sense described above. Plants should, therefore, not be humanized by such erroneous claims (Mallatt et al., 2020, 2021; Van Volkenburgh et al., 2021).

Even though lacking any indication for cognitive processes, plants clearly show adaptive "behavior." Leaves turn toward the sun, Venus flytraps capture and digest insects, and root tips grow toward well-suited sites providing stability and sufficient nutrients. All this, however, does not require any internal deliberation process that even comes close to genuine thinking or decision-making. Therefore, as long as no positive evidence is presented, we can and should assume that there is “no one at home” in the plant, regardless of whether we talk to them or not. They will not tell us their feelings and thoughts because they have none (Taiz et al., 2019). This does not lessen our fascination for the amazing, sometimes mysterious, and extremely rich adaptations of plants to their environment. It also leaves room for a respectful, preserving and even emotional interaction with these creatures. However, the bizarre discussion about plant brains and plant consciousness reflects a purely anthropomorphic movement: by transferring intelligence and mindfulness to plants they gain quasi-human properties and, hence, an increased moral status. With this, “*Plant Neurobiology*” is in the process of creating a completely evidence-free scientific myth owed to the zeitgeist. Whether this serves plants better than a realistic understanding of these organisms in their own right is questionable. As a general conclusion from this example we note that adaptation of a living being to its habitat is not sufficient for the attribution of intelligence. Intelligence includes mental processes, freedom of choice, and intention-driven agency.

2.2 Movement Makes You Smart: The Origins of Intelligence

According to the above, an intelligent organism must therefore be able to grasp what is relevant in a situation, it must have various options to act, and there must be a cognitive process between the external cue and the reaction. The latter defines a “mental space” that is detached from perception or motor activity—it is exactly this middle level which distinguishes intelligent behavior from automated stimulus–response schemes (such as reflexes). Its location, for all we know, is the brain. Therefore, the question of intelligence inevitably leads to the question of the origin of centralized nervous systems in the animal kingdom (Miller, 2009). Nervous tissue has evolved in three of the five phyla of multicellular animals, namely the ribbed jellyfish (*Ctenophora*), cnidarians (*Cnidaria*), and bilaterians (*Bilateralia*, this group includes most animals with a habitually symmetrical structure such as fish, birds, mammals, crustaceans, spiders, and insects). In contrast, sponges (*Porofera*) and Placozoa (millimeter-sized multicellular “disc animals”) do not have nervous systems. In fact, they may even have lost this organ during their evolution (Ryan & Chiodin, 2015). Strikingly, animals equipped with a nervous system are generally mobile, i.e., able to move actively in the environment. Sponges and Placozoa, on the other hand, either cannot move at all or they do so only in an uncoordinated, amoeboid manner. Therefore, many authors see a close connection between active sensorimotor behavior and the evolution of nervous systems. This is readily illustrated with the well-known story of sea squirts, which start as a freely swimming larva which, of course, are equipped with a brain. When they mature, they attach to a rock and continue as sedentary animals—at this time, they digest their brain because they no longer need it. This story is amusing, especially when garnished with ironic analogies about sedentary lifestyles in humans. In the above form, however, it is exaggerated—adult sea squirts still have a central ganglion and possess sensory as well as motor neurons to coordinate their feeding behavior, reproduction and simple protective reflexes. Thus, they mainly use their simple nervous system to procreate, protect themselves, and regulate their internal environment, similar to our gut nervous system. Hence, we can confidently say that they are unlikely to have more intelligence than our digestive system. Larval sea squirts, on the other hand, are actively moving organisms with a rich behavioral repertoire and far more complex interactions with their environment. This is why they need a far more elaborate nervous system.

How does the brain support adaptive and flexible behavior? What do we really mean by "information processing"? Colombian-American neurophysiologist Rodolfo Llinas points out that brains primarily enable prediction (Llinas & Roy, 2009). They do this by integrating actual sensory input with past experiences and creating projections into the future. These future scenarios are then used to instruct behavior. In many cases, these processes occur subconsciously—imagine, e.g., a tennis player reacting to his opponent's service. In other cases, we might explicitly and consciously think about potential outcomes, e.g., when we take a major professional decision. Many situations of daily life are probably somewhere between both extremes. In all cases, the demands for information processing are high. This applies even in the apparently simple sensory–motor task of the tennis game: First, we need to filter the huge amount of sensory input to focus on the relevant bits—e.g., our opponents arm position, or the direction of his gaze. We must ignore the vast majority of available information, e.g., position and movements of any spectators, the color of his clothes etc. This filtering, in turn, is an active process guided by attention (focusing on the opponent's position and movement, and filtering out what happens in the periphery of our visual field) and by experience (a professional tennis player will spot the important bits much earlier, and predict the direction and speed of the service much more accurately than a beginner). In more complex situations, rules may be involved, i.e., generalized patterns to which the actual situation has to be mapped. Imagine, e.g., a major consumer decision such as buying a new car. In addition to actual information about different offers and prior knowledge about cars, we will also make use of general guidelines ("never buy the cheapest item," "compare additional costs for service and insurance," "don't decide without consulting your partner," etc.). Choosing the best rule for a given situation, and switching to other rule sets when the previously used guidelines are not successful, is a hallmark of intelligence. Cognitive and behavioral flexibility are linked to certain brain regions (most importantly the frontal parts of the neocortex), and they differ between species and individuals (as visible from the distribution of intelligence quotients in human populations). In summary, information filtering, experience-dependent learning, application of rules, and flexible rule switching work together to enable successful, adaptive behavior. Complex decisions can be imagined in a virtual mental space, detached from the outside world and, hence, open to trial and error. All these processes are heavily dependent on the structure and activity of the brain. Hence, the richer the behavioral repertoire of an organism, the more elaborate is its brain. This is why freely swimming larvae need a real brain, while adult sea squirts get along with a small ganglion. Bottom line: if you don't move, you don't really need a brain.

2.3 Scala Naturae?

While we have emphasized the behavioral flexibility of sea squirt larvae, most of us would probably agree on the statement that we are far smarter. The diversity of potential behaviors, the ability to imagine and plan, and the capacity to learn are clearly more developed in humans than in sea squirts. In general, cross-species comparisons show that human intelligence has developed in a very special and elaborate way. Our brain accounts for approximately 15–20% of total energy consumption at rest. We are born very immature, and it is mainly the maturation of the brain that keeps us in parental care for more than a decade. As a species, we have changed our environment so much that we speak of the present geological time as the "Anthropocene." Thus there is no doubt that the human species has a unique behavioral range and a similarly unique impact—including, unfortunately, the destructive consequences of our industrial culture.

The extreme position of humans in comparison to all other species is, by all available knowledge, strongly coupled to the brain. It is not clear, however, why and how the brain of hominids took this evolutionary course. The respective theories can be roughly divided into physical and sociocultural lines of arguments (summarized in Hofman, 2019). Some authors hypothesize that changing environmental conditions (climate, food availability, etc.) required rapid adaptive processes by early hominids (Rosati, 2017). This, they argue, exerted a strong evolutionary "pressure" to enhance behavioral flexibility, especially because we do not have highly specialized biological adaptations, but are rather generalists. Other authors emphasize the importance of group processes, which has turned communication and learning in a social context into key faculties (Herrmann et al., 2007; van Schaik & Burkart, 2011). This gave rise to an increasingly sophisticated language and an expansion of the internal imaginative space, i.e., thinking. From there, it is not far to the formation of culture. This collective system of knowledge and practices develops in a process often called "cultural evolution" which progresses much faster than biological evolution. As a result, we cope with technology, art and culture at today's level with a brain whose modern structure formed 200,000 to approx. 35,000 years ago (Hauser et al., 2014; Stern, 2017; Neubauer et al., 2018). Keeping this in mind helps avoid anthropocentric and overly self-confident views of ourselves compared to other species. Animals, especially primates, are our close relatives, much closer than we like to think at times.

As stated above, and as visible from many clinical conditions, an intact nervous system is a prerequisite for "biological intelligence," a term frequently used to distinguish intelligence in an evolutionary context from artificial intelligence. However, the mere existence of a nervous system is not sufficient for "higher" forms of cognition. Our intestinal ("enteric") nervous system, for example, would not be a good substitute for our neocortex when it comes to complex, conscious decision-making. How does, then, the structure of a nervous system correlate with its function, and what are the neuronal determinants of intelligence? This question is one of the most exciting problems in neurobiology, and, as might be expected, there is no simple answer. It is even not easy to define what we mean by "true" or "higher" cognition when referring to humans as opposed to, e.g., sea squirts. While we have pointed out that there are indeed differences in behavioral and cognitive flexibility between species, commonly used terms suggest a hierarchical order which should, at least, be explicitly reflected. This hierarchy has a long-standing history as the so-called "*scala naturae*", and it is still effective in modern science. But is there really an ascending order of intelligences, beginning with sea squirt larvae and going via insects, frogs, dogs and apes all the way to man? How would such a hierarchy be defined and measured? Is it linear? What happens at evolutionary branch points? Is the whole concept just another proof of our anthropocentric attitude? Are other forms of life just differently adapted to the environment, but not standing below humans in any meaningful hierarchy? The answer to these questions is, as so often, an informed "yes" rather than a bold headline.

Animals show a very wide range of behaviors, including flexible problem solving, which, according to our definition, clearly indicates intelligence. Because animals do not speak in the same sense as humans, we have no direct access to their "thoughts" and rely on measures at the behavioral level. This requires defining behavior-based criteria for measuring intelligence, each of which must be operationalized in experimental protocols and observable variables (Manger, 2013). Established criteria for intelligence are, for example, tool use, understanding of quantities, complex social structures, learning by imitation, innovative problem solving, and insight into the intentions of others. In some cases, scientists also test the ability to learn language, and the ability to recognize one's own image in a mirror. The latter is interpreted as an indication of self-awareness and is only detectable in a few species (elephants, dolphins, great apes, and certain birds).

In all these categories, animals show astonishing achievements, which one can hardly deny the predicate of intelligent behavior. Particularly outstanding cognitive abilities are found in the great apes, as well as in corvids and parrots. In contrast, the mental capacity of whales, dolphins, and porpoises (cetaceans) is more controversial, partly triggered by exaggerated statements on the "wisdom of whales" in popular literature. Experts paint a nuanced picture, pointing to our still incomplete knowledge as well as the differences between toothed and baleen whales (the former are presumably much more intelligent). Overall, there is no doubt that there is very flexible behavior and cognition in cetaceans (Manger, 2013; Güntürkün, 2014). However, all animals, even the most intelligent ones, have a large gap to human performance. Especially in linguistic abilities, abstractions, and tool use, we are clearly superior to all our relatives.

3 What Makes an "Intelligent Brain"?

3.1 Is Big Beautiful?

There is undoubtedly a relationship between "biological" intelligence and the brain. However, can one directly infer the intelligence of an animal from its brain structure? Is the connection causal? Do we understand the underlying neural processes? Are humans distinguished from animals by degree or categorically? Such questions on the biological foundations of mental capacities and on the uniqueness of humans run throughout the history of brain research. The physician and early brain researcher Franz Joseph Gall, for example, established a system where he located personality traits and talents in certain regions of the brain. Most of these "faculties" he found (or postulated) at similar places in humans and animals. The kinship between animals and humans in mental or even intellectual matters was scandalous at the time, leading to a ban on teaching his materialist doctrine by the Austrian Emperor Franz II in 1802. Modern neurobiological research places most of Gall's contribution into the realm of speculation and pseudo-science, but has no problem accepting the fundamental kinship between humans and animals. Nevertheless, the debate on materialism lives on in other contexts, such as the question of free will or the consciousness of machines.

With respect to intelligence, it is proving extremely difficult to precisely define those properties of brains that correlate with strong cognitive abilities and behavioral flexibility, especially when comparing different animal species and humans (for a review, see Dicke & Roth, 2016). Early attempts simply took brain weight as a proxy for intelligence. In fact, there is a gradient between humans and their closest relatives that correlates well with estimates of intelligence—at 1200–1400 g, we are at the top of this group, followed by great apes at up to just under 600 g, and other primates at mostly under 200 g. Hominid skull finds also suggest brain growth in human evolution, with Neanderthals even having slightly heavier brains than modern humans. However, once we look more broadly into the animal kingdom, the comparisons are less conclusive—for example, the brains of elephants, walruses, and whales are significantly heavier than those of humans. According to Dicke and Roth (2016), mammalian brain weights range from 0.074 g (bamboo bat) to 10,000 g (sperm whale, orca). It is unlikely that this over 100,000-fold difference is proportional to their differential intelligence. Indeed, further research showed that the differences in brain weight can be explained to 90% by differences in body weight. Attempts have been made to factor out this effect by the brain weight/body weight quotient, but even this did not produce a useful measure. The blue whale now slips to one of the last places with a brain comprising only 0.005% of its body weight, while small mammals are at 10% and humans at 2%. The reason for these discrepancies is that brain weight does not increase linearly with body weight, but more slowly. The encephalization quotient proposed by H. Jerison takes into account this correlation within each class of animals and asks whether, in a given species, brain weight is below or above the trend characteristic of that group (Jerison, 1973). This comparative figure correlates better with observed behavioral flexibility or intelligence. Humans now top the list with a relative brain weight seven times above the expected value. However, even this measure is not perfect, showing significant deviations from a plausible arrangement in several species. In short, there is no simple measure of brain structure to predict cognitive abilities across species. For sure, the simple motto "big brains make intelligent" is nonsense.

Research on brain–intelligence relations has progressed in two main directions: firstly, scientists have asked which parts of the brain have a particularly strong influence on cognitive performance, and secondly, attempts have been made to correlate intelligence with the fine structure of neuronal networks (Kaas & Herculano-Houzel, 2017). The first approach, not surprisingly, leads to an emphasis on the mammalian neocortex (brain mantle or simply "cortex"). In fact, the volume of the cortex in humans is disproportionately large compared to other species. This does apply even more for the frontal cortex, which is quite prominent in primates and especially in humans (Semendeferi et al., 2002). Other authors additionally emphasize the importance of areas in the parietal lobe and suggest the frontoparietal complex as a crucial region for mental performance in humans. With some caution against over-simplification we may say that the (pre)-frontal brain is particularly important for action, decision-making, and rational impulse control, while the parietal cortex integrates multimodal sensory and motor impulses and in this way generates our picture of the current context. Both areas are so-called association cortices, i.e., they do not receive direct sensory input or generate immediate motor output. The relative extent of these association areas is exceptionally high in humans, whereas animals with more restricted behavioral repertoires have predominantly primary sensory or motor areas with direct connections to the periphery (Fig. 2.1). In a sense, association areas are relatively detached from the external reality, providing an additional level of neuronal activity whose mental correlate can be described figuratively as the "inner space" of cognition.

When discussing such localizations we should be careful to avoid simplistic identifications. Brain structures and mental processes are not identical but belong to conceptually different categories (biological structures versus mental functions). We should also keep in mind that the brain works as a network, so that all relevant cognitive processes require activation of numerous interacting regions. Therefore, we can at best assign a special relevance of specific brain areas for certain functions, but never an identity. This does also pertain to brain areas "below" the neocortex. Observations in neurological patients, for example, indicate that the cerebellum contributes significantly to cognitive performance, in addition to its undisputed motor function (Schmahmann, 2010). Similarly, the basal ganglia (a group of nuclei underneath the cortex) are of key importance for initiation and selection of actions, and for behavioral flexibility. While they are clinically best known for the associated movement disorders, they are equally important for these cognitive functions. Thus, neurodegenerative diseases of the cerebellum or basal ganglia can (but need not!) cause severe intelligence deficits in addition to more somatic neurological symptoms.

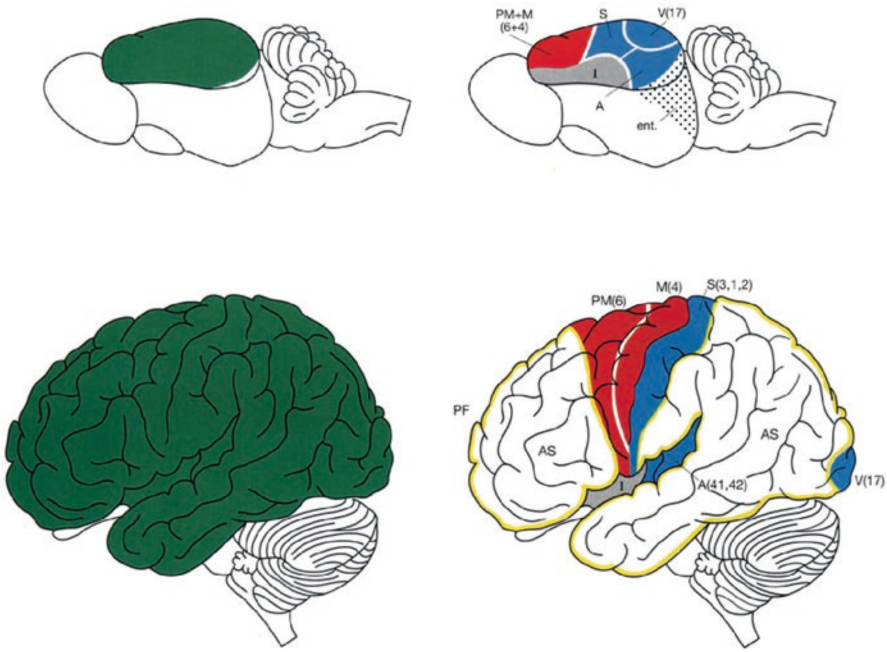

Fig. 2.1 Comparison of the brain of a human and a hedgehog. In the schematic sketches, the neocortex is colored green, motor areas red, and sensory areas blue. In the left part of the figure, the dominance of the neocortex in humans is striking, the area of which is further enhanced by the convolution. The right part shows that the hedgehog's cortex consists mainly of areas that have direct sensory or motor functions. In humans, in contrast, the majority of the cortex is association cortex with areas not directly connected to peripheral sensors or effectors (white areas). (Reprinted from Hofman, 2019, with kind permission of the publisher)

3.2 A Look at the Inner Workings of the Brain: Neuronal Networks

Anatomical subdivisions of the brain do provide some clues to the structural basis of intelligence, but they are clearly insufficient to explain the differences in performance between and within species. A complementary and very powerful approach is to look at the fine structure of neuronal networks (Sporns et al., 2000). The fundamental structure of the cortex is quite similar in all mammals, with the dominant feature of several (usually six) interconnected layers of neurons. However, at a finer scale there is considerable variation between species, and within each species there are differences between functionally specialized areas. This heterogeneity is reflected in the different thickness and cell numbers of each layer, which was already described over 100 years ago and hypothetically interpreted as functional specialization (Brodmann, 1909). Several parameters of neuronal networks have been proven to be relevant determinants of intelligence: the number of neurons, their density, the number of synapses, and, last but not least, the thickness of axons. The latter are the “cables” which transmit electrical impulses between neurons, and their thickness determines conduction speed which seems to offer a decisive advantage for fast information processing. Conduction velocity is also increased by covering the axons with sheaths of so-called “glia cells” which, in turn, are likely to make an important contribution to intelligence. The role of glia cells has been underestimated for a long time, led by a “neurocentric” understanding of the brain and inspired by the widely used metaphoric language of neuronal “circuitry,” “signals,” etc.

Multiplying the area and thickness of the cortex by the average neuron density, we arrive at the total number of neurons, which is maximal in humans (~15 billion), followed by elephants, apes, and orcas. However, these numbers are subject to large methodological uncertainties. The same is true for the number of synapses, which can only be roughly estimated. Individual neurons typically receive thousands or tens of thousands of synapses from other cells, underscoring the enormous complexity of neuronal networks. Using state-of-the-art microscopic and computational methods, attempts are now being made to reconstruct individual brain regions as completely as possible. However, this proves to be a major experimental and data-analytical challenge, and there is still a very long way to go before a comparative overview of all relevant cortex areas in numerous species is available.

Incidentally, micro- and macrostructure and the function of the cortex are related in several ways. A widely known property is the strong folding of the cortex in humans, resulting in the characteristic ridges and furrows (scientifically called *gyri* and *sulci*). Folding is likely an adaptation to the evolutionary increase in total cortex area. The increased cortex must fit within the limited space of the cranial capsule (which in turn is limited by entirely different factors such as the female birth canal). As an additional effect, folding of the cortex allows for particularly high local connectivity because neurons are thus brought closer together (Herculano-Houzel et al., 2010). Short conduction paths, in turn, increase the processing speed in networks, which we have already identified as an important determinant of intelligence. By the way, connectivity seems to become a major limiting factor in cetaceans, so that these giant animals have a rather thin cortex and a high volume of the underlying white matter (which contains the axons). Indeed, the required space for connections increases supra-linearly when the number of highly connected neurons increases. This geometric problem may be a limiting factor for brain evolution in general, and for the giant brains of cetaceans in particular.

Finally, the modular structure of neuronal networks is characteristic: nearby neurons are highly interconnected and form functional units, whereas remote connections are much rarer (Sporns & Betzel, 2016). Again, this limitation is a necessary consequence of the extreme space demand for connections. Imagine that every neuron in our brain would be directly connected to every other neuron—this would drive the required volume of white matter beyond any conceivable measure. On the other hand, modern methods of the young “network science” show that combining high local connectivity with much lower long-range connectivity allows very efficient communication across the entire system. This *small world* effect is impressively demonstrated in social networks: When we meet a random person abroad it is not uncommon to find mutual acquaintances. The underlying reason is that we are highly connected in our local (social) environment. It suffices if one of our contacts has a long-range connection to the local network of the encountered person, and the connection is (almost) made. In fact, we are connected to the vast majority of other people worldwide via less than ten intermediate stations.

Another consequence of the high local connectivity is the formation of modules. The modularity of the brain reflects the structural and functional specialization of different areas (Brodmann, 1909; Dicke & Roth, 2016; Hofman, 2019), which is the basis for the above-mentioned localization theories of mental processes. When we look in detail into the modules or functional domains, characteristic differences between species become apparent, some of which can be directly linked to differences in behavior. This is most easily seen in those areas that are closely coupled to sensory or motor functions. It is no coincidence that sound- and language-processing cortexes are particularly prominent in humans, visual cortex areas dominate in cats, and rodents have a relatively large representation of olfactory cortices. Possibly, the modularization and specialization of cortex areas described above is also a reason for the hemispheric asymmetry in humans, in which, for example, language processing takes place predominantly on the left side. In animals with less specialized cognitive abilities, e.g. rats, this asymmetry is much weaker.

All theories on the connection between cortex architecture and intelligence face a massive problem: birds. At first and second glance, the brains of these animals have little in common with those of mammals; above all, they have no typical neocortex (Fig. 2.2).

Nevertheless, corvids (*Corvidae*) and parrots (*Psittaciformes*) reach the intelligence of apes. They use tools, can learn highly differentiated communication by

Fig. 2.2 Different brain architectures for comparable performance. Intelligent behaviors such as tool use, flexible problem solving, complex communication, and understanding quantities are comparable in monkeys and corvids. Nevertheless, their brain structures are fundamentally different. Only recently the "nidopallium caudolaterale" has been identified as functionally equivalent to the primate prefrontal cortex. (Reprinted from Nieder, 2016, with kind permission of the publisher)

language, are creative problem solvers in nature as well as in the laboratory, and are amazingly good at “arithmetic” (Nieder, 2020). How can it be that such cognitive features arise from so different brain architectures? Recent research tends to suggest that the avian brain mantle does share essential characteristics of the mammalian neocortex in terms of neuronal connectivity and efficiency (Stacho et al., 2020; Herculano-Houzel, 2020). This applies particularly to the *nidopallium caudolaterale*, which is indispensable for complex and flexible behaviors. It is precisely in this network that cell types and connectivity patterns resemble those of the primate (frontal) cortex. Such similarities and divergences between species give valuable insights into the biological conditions of intelligence. Similarly instructive are reports from humans with malformations of the cortex. Some of these individuals exhibit relatively high intelligence and are perfectly able to cope with their lives (Feuillet et al., 2007). Unfortunately, such fortunate cases are the exception, while many cortical lesions and maturational disorders are associated with significant intelligence deficits, making increased insight into the underlying mechanisms even more pressing.

3.3 Crown of Creation?

There is a strong and long-standing tradition to emphasize the importance and particularly large size of the (pre)frontal brain in humans. Indeed, the frontal, and especially the prefrontal, cortex of different species correlate to some degree with our intuition of intelligence and cognitive flexibility. The human prefrontal cortex also stands out in terms of its network structure, containing a particularly cell-rich layer 4 (the so-called granular layer after the fine-grained appearance in microscopic images; Elston et al., 2006; Donahue et al., 2018). Increasing “frontalization” is often presented as evidence for the special evolutionary position of humans, although we have already pointed out that localization theories of mental functions should be applied with caution, an even more so the anthropocentric idea of a *scala naturae*. The localization of all “higher” mental functions in the frontal lobe has led to horrible medical practices in the twentieth century. Since the 1930s, the difficult-to-treat patients with schizophrenia, obsessive–compulsive disorder and other mental illnesses have been treated “psychosurgically” by the thousands. The standard “therapy” was leucotomy (“cutting of the white matter”) or lobotomy (“lobe severance”). With this gross and debilitating procedure, the connections of the frontal brain with the thalamus and with other cortex regions were largely eliminated. The new method was even valorized by the Nobel Prize for Physiology or Medicine, which was awarded to the Portuguese António Egas Moniz in 1949. At the time, it was considered a great therapeutic breakthrough. The fact that the patients suffered severe personality disorders and the loss of motivation and pleasure for the rest of their lives did not lead to the end of this fatal aberration before the 1960s and even the 1970s.

To this day, reflections of the Aristotelian ideal of the human being as *zoon logicon* (or *animal rationale*) can be found in literature on the frontal cortex. This includes moralizing statements according to which only an intact (pre)frontal cortex prevents us from acting libidinously, selfishly, aggressively, criminally, and generally in a manner detrimental to the community (Wise, 2008). As an organ of "executive control," the prefrontal cortex is closely associated with cognitive problem-solving strategies and, therefore, with human intelligence. The emphasis on this brain region may often be overstated but is not entirely implausible, as lesions of the prefrontal cortex can indeed result in decreased impulse control, changes in personality, and reductions in the ability to make rational decisions. Critically, however, one should call for attention to the categorical distinction between moral values and brain-based behavioral dispositions. The thinking, deciding, and acting subject is a person, not a brain (Janich, 2009). As persons, however, we are not independent of our body and, in particular, our brain.

Could further evolution result in humans with an even larger and more efficient cortex and, hence, even greater intellectual abilities? The potential for further growth of the brain seems to be limited—our large and cell-rich cortex has already evolved at the cost of a substantial, disproportionate increase in white matter (i.e., the "cables") (Rilling, 2014). Size and connectivity cannot be increased at will, as can be seen in the particularly thin cortices and large white matter volume in whales. Moreover, at approximately 2% of our body weight, the brain already consumes over 15% of our energy, and its maturation takes until the third decade of life. Theorists even predict that the brain's intense metabolism will cause significant problems of heat dissipation if it continues to increase (Bullmore & Sporns, 2012; Hofman, 2019). Thus, issues of space requirements, energy consumption, and temperature regulation may become limiting factors for further development. It will be interesting to see whether and when similar problems arise in computing and artificial intelligence.

4 Fine Distinctions: Why Aren't We All Equally Smart?

4.1 Clever Minds?

Until now, we focused on the relationship between brain structure and function in different species. But what about variance within the human species? Three questions have long preoccupied researchers: Is there a structural or neurophysiological correlate of different levels of intelligence in humans? Are different levels of intelligence innate or acquired? Can intelligence be increased or harmed during childhood and later life?

"Intelligence" is a scientific construct within psychology, not a primary physical property of the brain. Nevertheless, similar to our considerations on differences between species, we must expect that intelligence within the human species is also not independent of the brain. This is immediately visible from disorders. Neurodegenerative processes such as Alzheimer's disease lead to an irreversible loss of intelligence in parallel with the loss of neural tissue. Many further congenital or acquired disorders of the brain impact on intelligence, depending on the extent and location of the damage. For example, damage to the primary visual cortex results in anopsia (inability to identify visual objects) in one half of our visual field. This loss of function certainly does not affect general intelligence. In contrast, diffuse damage of associative cortex areas (e.g., frontal or parietal brain lesions following prolonged lack of oxygen supply) has more severe effects on personality, behavior, and intelligence. Such examples from pathology are instructive, but also quite extreme compared to variance of cognitive abilities in the healthy population. Moreover, they tend to result in a simplified logic: "When *X* fails, function *Y* is regularly affected, so *X* is important for (or even causes) *Y*." Complex functions do, however, arise from systemic interactions between multiple regions and system levels. A linear, monocausal principle of bottom-up causation is clearly less complex.

Nevertheless, there are identifiable structural and functional factors accounting for differences in intelligence between healthy humans. These include, first of all, the size of the brain, which we had already learned about in the comparison of different species as a relevant but very coarse measurement. Attempts to correlate intelligence and brain size date back to the beginnings of neuropsychology. For example, the British naturalist Sir Francis Galton published an essay on "Head growth in students at the University of Cambridge" (Galton, 1888). As expected, the correlation between brain volume and intelligence in humans becomes stronger if one focuses on the cortex instead of the whole brain, especially on the important frontal and parietal association areas (Jung & Haier, 2007). Another interesting correlation has been shown using functional imaging methods, a dominant approach in modern cognitive neurosciences. Measurements of metabolic activity showed that brain energy consumption correlates negatively with intelligence. To put it loosely, the more intelligent a person is, the less effort it takes him or her to solve a given problem. Thus, cognitive performance appears to be a matter of efficiency, similar to physical exercises that a trained athlete completes with ease, while an untrained person reaches his or her limits (Neubauer & Fink, 2009).

There are also interesting new insights at the structural level. For example, recent studies using high-resolution techniques indicate that the density of neuronal branches ("dendrites") is lower in individuals with higher intelligence (e.g., Genç et al., 2018; Fig. 2.3). This finding points to less, rather than more, synaptic interactions, which is against our intuition. However, it may be that particularly powerful and efficient networks maintain only those connections which have proven to be important while other "distracting" connections are lost.

Thus, there seems to be an optimum of connectivity, in line with the principle of "sparse coding," according to which only a small minority of neurons is active in neuronal networks at any given time. In fact, during childhood, we do not just form new synapses but erase those that are not regularly used to a large extent! This synaptic "pruning" is an experience-dependent maturation process that leads to the preservation of only those connections which are functionally important. As a result,

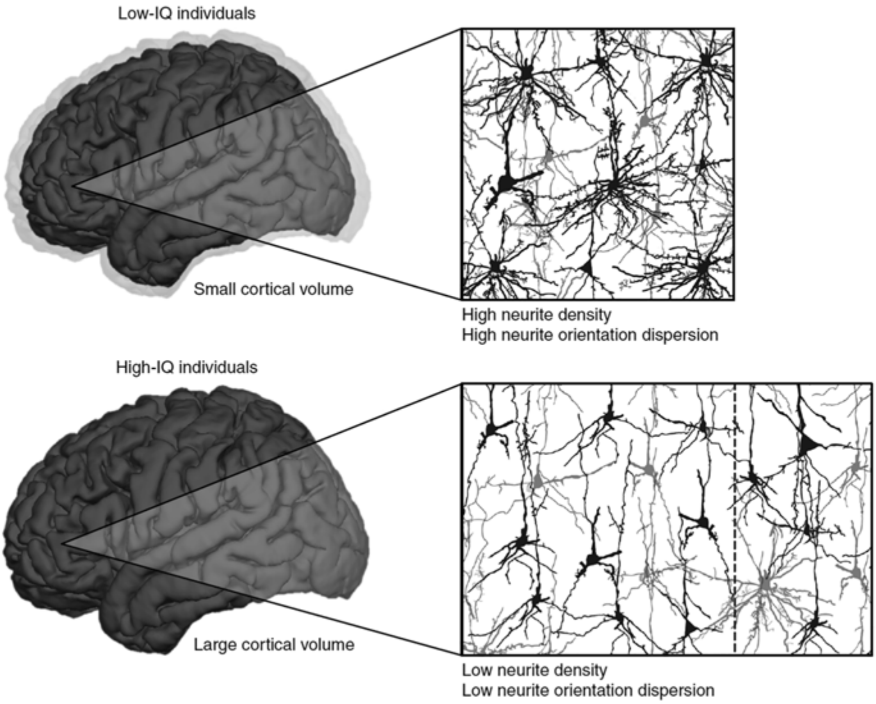

Fig. 2.3 Individual intelligence and cortical networks. Structural correlates of intelligence are not easily defined between or within species. The figure summarizes results of a recent study showing that individuals with higher intelligence have a larger neocortex than those with lower IQ. However, the fine structure shows a much lower complexity of neuronal projections at the sites of signal transmission. Presumably, in the higher-performing brain, functionally important connections have been selectively strengthened and arranged in a particularly efficient manner. (Reprinted from Genç et al., 2018, under "Creative Commons License")

we might find higher intelligence in individuals with lower connectivity, at least within certain limits. More importantly, the necessity of network-level remodeling processes during maturation provides a physiological rationale for the requirement to raise children and adolescents in a rich environment. Maturation of the brain requires exposure to multiple sensory, motor, and intellectual cues and challenges! Any sensory, motor, or social deprivation in children is damaging and has to be treated with utmost care and efficacy. There are limited time windows for each step of these adaptive changes. At later stages, plasticity is strongly reduced!

4.2 Nature via Nurture

We have seen that there are physical correlates of the different intelligence of people, both on a structural and on a functional level. To which degree can we influence these parameters, and to which degree are they innate? The "nature–nurture" problem has long preoccupied science and the public, not least because it has major implications for our self-understanding and for (educational) policy concepts. Studies on twins have been instrumental in the respective research efforts. Of special importance were those twins who grew up in different environments after being adopted. These individuals were genetically identical but exposed to different environments—a perfect quasi-experimental setting to study the nature–nurture problem. Overall, these and other studies have revealed a strong influence of genes on intelligence (with large variations in estimates between ~30% and 80%). However, these statements need additional comments and explanations. First, there is no such thing as "the" intelligence gene—all individual gene variants contribute only minimally to the differences in intelligence. Thus, as far as genetics is involved, intelligence has a complex, polygenetic trait. Second, most of the studied twins grew up in very similar environments. This is true even in the case of adopted children, which were usually placed in typical middle-class families with a rather high level of education. Thus, their experiences were similar and did not uncover the full range of environment-driven variability. Therefore, the relative weight of genetic determinants was systematically overestimated. Third, we now know that genetic factors are not as deterministic as previously thought. Rather, interaction of an organism with the environment has repercussions on gene activity, including lasting and inheritable alterations. These mechanisms are referred to as gene regulation, epigenetic factors, and gene–environment interactions. Therefore, instead of a *nature versus nurture debate*, the British author Mat Ridley has proposed a *nature via nurture debate* (Ridley, 2003, quoted in Stern, 2017).

There might be another distortion similar to the statistical artifact caused by the highly homogeneous living conditions of separately raised twins: the measurable influence of genes is lower in socioeconomically weak strata than in richer environments. The likely reason is that in the (quantitatively dominating) middle classes of Western industrialized countries nutrition, education, health care, etc., are largely uniform. This means that there is less environmental variance, so that genetic variance has an apparently stronger influence in these groups. In poorer societies, on the other hand, there is more variance in living conditions, so these factors have a greater impact. The fact that a stronger genetic component is found in older than in younger people can also be explained in this way—our living conditions become more stable and less heterogeneous with increasing age. Thus, the question of genes versus environment as determinants of intelligence is interesting and multi-faceted. It has no definite, and certainly no simple answer, and present knowledge certainly does not justify fatalism. We can do a lot to allow people developing their full potential, especially in children and adolescents who deserve positive, stimulating conditions (Stern, 2017). Even in elderly people, the brain is still plastic and benefits from an inspiring and moderately challenging environment.

This brings us to the final question: What can we do to promote intelligence, and what should be avoided? Again, we start with a look at pathology. A child's intelligence can already be prejudiced during embryonic development—an important example is congenital iodine deficiency syndrome (formerly called cretinism), which leads to mental retardation. In contrast to the sad reality, this condition should be eliminated on a worldwide scale, due to the easy and cheap prophylaxis (supplying sufficient iodine to the mother). Other mechanisms of early damage are maternal alcohol consumption or (in this point less dramatic) smoking during pregnancy, malnutrition, or psychosocial neglect of young children. An extreme example is the syndrome of hospitalism occurring in severely neglected children in care that show massive reductions in intelligence and social behavior. In turn, attention, stimulation, and encouragement have clear positive effects not only on intellectual but also social abilities of children. Institutions can, to a limited degree, compensate for disadvantages of those who lack support at home. This begins with a good nutrition (still not available to all children even in developed countries), and continues to language acquisition (especially for children with a migration history), reliable relationships with children and adults, and the above-mentioned training by variably and stimulating cues and tasks. Poor starting conditions create disadvantages and require intense and early institutional support. While the proverb "You can't teach an old dog new tricks" is more fatalistic than modern neurosciences would posit, it is not entirely wrong either.

To summarize: Our intelligence can only fully develop in good external conditions, including diverse stimuli and supportive social interactions. This is of particular importance in the first years of life. It goes without saying that this well-documented scientific insight must have consequences for the design of opportunity-oriented education systems, as well as on social welfare and health care institutions.

References

Brenner, E. D., Stahlberg, R., Mancuso, S., Vivanco, J., Baluska, F., & van Volkenburgh, E. (2006). Plant neurobiology: An integrated view of plant signaling. *Trends in Plant Science, 11*, 413–419.

Brodmann, K. (1909). *Vergleichende Lokalisationslehre der Grosshirnrinde in ihren Prinzipien dargestellt auf Grund des Zellenbaues*. Barth.

Bullmore, E., & Sporns, O. (2012). The economy of brain network organization. *Nature Reviews. Neuroscience, 13*, 336–349.

Dicke, U., & Roth, G. (2016). Neuronal factors determining high intelligence. *Philosophical Transactions of the Royal Society B: Biological Sciences, 371*, 20150180.

Donahue, C. J., Glasser, M. F., Preuss, T. M., Rilling, J. K., & Van Essen, D. C. (2018). Quantitative assessment of prefrontal cortex in humans relative to nonhuman primates. *Proceedings of the National Academy of Sciences of the United States of America, 115*, E5183–E5192.

Elston, G. N., Benatives-Piccione, R., Elston, A., Zietsch, B., Defelipe, J., Manger, P., Casagrands, V., & Kass, J. H. (2006). Specializations of the granular prefrontal cortex of primates:

Implication for cognitive processing. *The Anatomical Record Part A: Discoveries in Molecular, Cellular, and Evolutionary Biology, 288A*, 26–35.
Feuillet, L., Dufour, H., & Pelletier, J. (2007). Brain of a white-collar worker. *Lancet, 370*, 262.
Gagliano, M., Vyazovskiy, V. V., Borbély, A. A., Grimonprez, M., & Depczynski, M. (2016). Learning by association in plants. *Scientific Reports, 6*, 38427.
Galton, F. (1888). Head growth in students at the University of Cambridge. *Nature, 38*, 14–15.
Genç, E., Fraenz, C., Schlüter, C., Friedrich, P., Hossiep, R., Voelkle, M. C., Ling, J. M., Güntürkün, O., & Jung, R. E. (2018). Diffusion markers of dendritic density and arborization in gray matter predict differences in intelligence. *Nature Communications, 9*, 1905.
Güntürkün, O. (2014). Is dolphin cognition special? *Brain, Behavior and Evolution, 83*, 177–180.
Hauser, M. D., Yang, C., Berwick, R. C., Tattersall, I., Ryan, M. J., Watumull, J., Chomsky, N., & Lewontin, R. C. (2014). The mystery of language evolution. *Frontiers in Psychology, 5*, 410.
Herculano-Houzel, S. (2020). Birds do have a brain cortex-and think. *Science, 369*, 21567–21568.
Herculano-Houzel, S., Mota, B., Wong, P., & Kaas, J. H. (2010). Connectivity-driven white matter scaling and folding in primate cerebral cortex. *Proceedings. National Academy of Sciences. United States of America, 107*, 19008–19013.
Herrmann, E., Call, J., Hernandez-Lloreda, M. V., Hare, B., & Tomasello, M. (2007). Humans have evolved specialized skills of social cognition: The cultural intelligence hypothesis. *Science, 317*, 1360–1366.
Hofman, M. A. (2019). On the nature and evolution of the human mind. *Progress in Brain Research, 250*, 251–283.
Janich, P. (2009). *No new image of man. On the language of brain research*. Suhrkamp.
Jerison, H. J. (1973). *Evolution of the brain and intelligence*. Academic Press.
Jung, R. E., & Haier, R. J. (2007). The Parieto-Frontal Integration Theory (P-FIT) of intelligence: Converging neuroimaging evidence. *The Behavioral and Brain Sciences, 30*, 135–154.
Kaas, J. H., & Herculano-Houzel, S. (2017). What makes the human brain special: Key features of brain and neocortex. In I. Opris & M. F. Casanova (Eds.), *Physics of the mind and brain disorders* (pp. 3–22). Springer.
Llinas, R. R., & Roy, S. (2009). The 'prediction imperative' as the basis for self-awareness. *Philosophical Transactions of the Royal Society B, 364*, 1301–1307.
Mallatt, J., Blatt, M. R., Draguhn, A., Robinson, D. G., & Taiz, L. (2020). Debunking a myth: Plant consciousness. *Protoplasma, 258*, 459. https://doi.org/10.1007/s00709-020-01579-w
Mallatt, J., Robinson, D. G., Draguhn, A., Blatt, M. R., & Taiz, L. (2021). Understanding plant behavior: A student perspective: Response to Van Volkenburgh et al. *Trends in Plant Science, 26*, 1089–1090.
Manger, P. R. (2013). Questioning the interpretations of behavioral observations in cetaceans: Is there really support for a special intellectual status for this mammalian order? *Neuroscience, 250*, 664–696.
Miller, G. (2009). On the origin of the nervous system. *Science, 325*, 24–26.
Neubauer, A. C., & Fink, A. (2009). Intelligence and neural efficiency. *Neuroscience and Biobehavioral Reviews, 33*, 1004–1023.
Neubauer S, Hublin JJ, Gunz P (2018) The evolution of modern human brain shape. Sci Adv 4:eaao5961.
Nieder, A. (2016). The neuronal code for number. *Nature Reviews. Neuroscience, 17*, 366–382.
Nieder, A. (2020). Absolute numerosity discrimination as a case study in comparative vertebrate intelligence. *Frontiers in Psychology, 11*, 1843.
Ridley, M. (2003). *Nature via nurture: Genes, experience, and what makes us human*. HarperCollins Publishers.
Rilling, J. K. (2014). Comparative primate neuroimaging: Insights into human brain evolution. *Trends in Cognitive Sciences, 18*, 46–55.
Robinsin, D. G., & Draguhn, A. (2021). Plants have neither synapses nor a nervous system. *Journal of Plant Physiology, 263*, 153467.

Rosati, A. G. (2017). Foraging cognition: Reviving the ecological intelligence hypothesis. *Trends in Cognitive Sciences, 21*, 691–702.
Ryan, J. F., & Chiodin, M. (2015). Where is my mind? How sponges and placozoans may have lost neural cell types. *Philosophical Transactions of the Royal Society B, 370*, 20150059.
Schmahmann, J. D. (2010). The role of the cerebellum in cognition and emotion: Personal reflections since 1982 on the dysmetria of thought hypothesis, and its historical evolution from theory to therapy. *Neuropsychology Review, 20*, 236–260.
Semendeferi, K., Lu, A., Schenker, N., & Damasio, H. (2002). Humans and great apes share a large frontal cortex. *Nature Neuroscience, 5*, 272–276.
Singer, P. (2013). *Practical ethics*. Reclam.
Sporns, O., & Betzel, R. F. (2016). Modular brain networks. *Annual Reviews of Psychology, 67*, 19.1–19.28.
Sporns, O., Tononi, G., & Edelman, G. M. (2000). Connectivity and complexity: The relationship between neuroanatomy and brain dynamics. *Neural Networks, 13*, 909–922.
Stacho, M., Herold, C., Rook, N., Wagner, H., Axer, M., Amunts, K., & Güntürkün, O. (2020). A cortex-like canonical circuit in the avian forebrain. *Science, 369*, 1585.
Stern, E. (2017). Individual differences in the learning potential of human beings. *NPJ Science of Learning, 2*, 2.
Taiz, L., Alkon, D., Draguhn, A., Murphy, A., Blatt, M., Hawes, C., Thiel, G., & Robinson, D. G. (2019). Plants neither possess nor require consciousness. *Trends in Plant Science, 24*, 677–687.
Trewavas, A. (2016). Intelligence, cognition, and language of green plants. *Frontiers in Psychology, 7*, 588.
Van Schaik, C. P., & Burkart, J. M. (2011). Social learning and evolution: The cultural intelligence hypothesis. *Philosophical Transactions of the Royal Society B, 366*, 1008–1016.
Van Volkenburgh, E., Mirzaei, K., & Ybarra, Y. (2021). Understanding plant behavior: A student perspective. *Trends in Plant Science, 26*, 423–425.
Wise, S. P. (2008). Forward frontal fields: Phylogeny and fundamental function. *Trends in Neurosciences, 31*, 599–608.
Wohlleben, P. (2015). *Das geheime Leben der Bäume*. Ludwig.
Wohlleben, P. (2016). *The hidden life of trees*. Greystone Books.

Andreas Draguhn has studied medicine and, concomitantly, physics and philosophy at Bonn University. Following his dissertation and different postdoctoral positions in Germany and the UK he has been Chair of Neurophysiology at Heidelberg University since 2002. His research focuses on the function of neuronal networks, in particular coordinated activity patterns of neurons in the context of memory processes. He has been involved in several interdisciplinary initiatives, including fellowships at the Marsilius-Kolleg of the University of Heidelberg. Since 2008, he has been Vice-Director of the Interdisciplinary Center for Neuroscience (IZN) at Heidelberg University. From 2009 to 2017 he was a member/speaker of the Review Board "Neuroscience" of the German Research Foundation (DFG). He served as Dean of Studies (2014–2018) and Dean (2018–2019) of the Medical Faculty Heidelberg.

Chapter 3
The Intelligent Play with Chances and Selection

Claudia Erbar and Peter Leins

Abstract Regardless of whether a product is the result of organismic evolution or man-made, if it claims to be optimally functional while at the same time being economical, it is often given the adjective 'intelligent' in the current language. 'Intelligent', of course, refers only to the initiator: in the one case, evolution with its intelligent play with chances and selection; in the other, the creativity of the 'mammal' *Homo sapiens*. A certain parallelism in the construction and functionality of independently developed devices and systems is remarkable. Or constructions provided by nature serve as a model, which has led to bionics as a scientific discipline of its own. In this article, only a few intelligent problem solutions out of an enormous abundance will be demonstrated. At first, they concern everyday objects. They are, for example, salt shakers suitable for breakfast eggs, adhesive devices such as suction cups, sticking attachment pads and—above all—hook-and-loop fasteners. With regard to the stability of surfaces, especially in terms of scratch resistance, various possibilities can be demonstrated in the case of plants. Mechanical stability under the influence of strong forces, e.g. wind or weight load, is provided by a folded surface as we find in palm leaves, instead of a flat one. Folded structures closed into a cylinder allow a considerable change in volume while the surface area remains the same; such a bellow or accordion effect allows ribbed cacti to absorb water (in rain) or lose water (through evaporation) without causing tissue tension. Lightweight construction and yet stability are demonstrated by the huge floating leaves of the *Victoria* water lily. More safety in the event of a shipwreck by having as many tightly sealed bulkheads as possible is something technicians can learn from floating seeds. More safety when building houses in earthquake areas architects can learn from trees with buttress roots and from grass blades. Camouflage for protection or attack reaches the ultimate perfection in insects and spiders. Even flowers deceive and cheat by sophisticated (= intelligent) adaptations to certain behavioural patterns of insects for the purpose of pollination. Conclusion: Evolution is intelligent, but knows no ethics!

C. Erbar (✉) · P. Leins
Centre for Organismal Studies (COS) Heidelberg – Biodiversity and Plant Systematics, University of Heidelberg, Heidelberg, Germany
e-mail: erle@urz.uni-heidelberg.de; https://www.cos.uni-heidelberg.de/de/forschungsgruppen/biodiversitaet-und-pflanzen-systematik/prof-claudia-erbar; https://www.cos.uni-heidelberg.de/de/forschungsgruppen/professoren-im-ruhestand/prof-dr-peter-leins

R. M. Holm-Hadulla et al. (eds.), *Intelligence - Theories and Applications*,
https://doi.org/10.1007/978-3-031-04198-3_3

1 Introductory Remarks

Concerning human beings, intelligence is a conglomerate of factors linked to the central nervous system: ability to observe, passing on what is perceived using the cleanest (non-manipulated) language possible, processing and integration of sensory perceptions, learning capability, ability to be logical, plausible and reasonable, control of emotions, creativeness, empathy and many more. When using the term intelligence adjectivally (as in the title of this article), caution is advised; there lurks the 'danger' of a dubious approach offered, for example, by the 'Intelligent Design movement' in the USA. This merely tries to distract from simple-minded creationism with a pseudo-scientific mantle. While creationism assumes a creation of the world by the biblical God a few thousand years ago, the 'doctrine' of 'Intelligent Design' acknowledges the duration of the origin of organisms over many millions of years, but continues to assume that all living things—even the extinct ones—are direct (!) creations of the designer. The authors of the present article ask for indulgence that they—despite all tolerance—distance themselves from such an implausible mythological fantasy. Any fantasies that lead into the esoteric, such as the supposedly caring communication between plant species, do not belong here, of course.

In fact, optimally functioning constructions can be found everywhere in the plant and animal kingdoms. They are ultimately the result of organismic evolution, namely selection, dominated by the economic principle (= principle of optimization), against whose background merciless competition takes place (Leins & Erbar, 2010, 2018; Erbar & Leins, 2018). The 'mammal' *Homo sapiens* has created optimally or almost optimally functioning devices and systems with its intelligence, based on a highly complex brain structure, which also arose from organismic evolution. This happened according to the 'trial and error' principle based on creativity and involving logic or at least plausibility. In the process, it often turns out that human creations can be found somewhere in 'nature', e.g. in plants or animals. Or the other way around: natural objects serve as models for the construction of tools, devices and systems.

In this context, the universal genius Leonardo da Vinci is often cited as a pioneer in this field. In 1505, in his manuscript 'On the Flight of Birds' ('Sul volo degli uccelli'[1]), he presented an analysis of the wings of birds in order to construct an artificial flying machine. But it was not until the twentieth century that bringing together biology and technology gained in importance. A new scientific discipline was born, 'BIONIK' (the German portmanteau word is composed of 'BIOlogie' and 'TechNIK'; in English, the terms 'bionics'[2] or 'biomimetics' are used). Nowadays, bionics deals on a large scale with all conceivable techniques, ranging

[1] The manuscript sheets are part of the 'Codice sul volo degli uccelli', also known as the 'Codex Turin', in the 'Biblioteca Reale' in Turin (Italy).

[2] The English term bionics is derived from 'bios' (Greek for "life") and the suffix '-onics' meaning 'study of'.

from architecture, highly complex devices, e.g. for medicine, to robotics (= robotic technology) and artificial intelligence.

The first person in Germany to address the question ‘What can technology learn from biology?’ in an impressive and comprehensive manner was the zoologist Werner Nachtigall (e.g. Nachtigall, 1997, 2007, 2008; Nachtigall & Blüchel, 2000).

As a product of bionics, the self-cleaning effect in plants discovered by the botanist Wilhelm Barthlott gained a high popularity. The effect is based on the so-called ‘lotus effect’: Dirt particles are removed from highly hydrophobic surfaces, such as the leaves of the lotus flower (*Nelumbo nucifera*), simply by water drops rolling off (Barthlott & Ehler, 1977; Barthlott & Neinhuis, 1997).

The intension to transfer biological properties directly to technical constructions or systems, i.e. to produce a ‘one-to-one copy’, does not achieve the desired success in many cases. In the well-known ‘lotus effect’, minimalization of the droplet’s adhesion to the surface is achieved by wax-like micro- and nano-structures, which, however, are by no means able to cope with mechanical demands; therefore, these must be reproduced from more stable materials (resulting products are, for example, plastics, certain lacquers, facade paints on house walls). In addition to chemical properties, dimensions or size ratios can also reduce the success of direct copies. The cost-benefit ratio must also be right, and design and functional compromises must be taken into account, especially in complex systems. An intelligent approach is therefore required on the part of the designer. Be that as it may, in the following sections a few, but nevertheless easily comprehensible examples are presented from the vast abundance of optimal or—in the case of compromises—suboptimal problem solutions in plants and animals, irrespective of whether these served as models for technical achievements or merely find their parallel in human constructions.

2 Optimization as an Evolutionary Goal

A higher development of organisms is controlled by a principle, the economic principle or optimization principle, which determines selection. This principle becomes effective when organisms (individuals in a population or different species) compete in their different adaptations to certain environmental (abiotic and biotic) factors (‘survival of the fittest’, ‘struggle for life’, Darwin, 1859). The prerequisite is, of course, their difference in genetic make-up, which is due to purely random (!) mutations and recombinations; migrations and isolations (origin of new taxa) also occur randomly. ‘Competitive struggles’ take place in many cases on courtship grounds (also called lek) and breeding places. Figure 3.1 shows some scenes from the aggressive-turbulent sexual behaviour of the Sicilian mortar bee *Chalicodoma sicula*. The female ‘decides’ on when to mate and moves to a mating place—an area about one or a few m^2 in size, where some male mortar bees of different size and colouring (dark brown to grey) patrol, waiting for females. In Fig. 3.1a, a male—numbered with 1—has already grasped a female and is just copulating, as evidenced by rapid fanning with the wings for air supply. The females are larger than the

Fig. 3.1 Three males (1, 2, 3) and one female (♀) of the Sicilian mortar bee (*Chalicotoma sicula*) in four scenes on a mating site. See text for explanation. (Image credit: Own photographs)

males, which vary in size among themselves, and possess blue-iridescent wings and strong mandibles (to be seen in Fig. 3.1c).[3] It doesn't take long for competitors to appear—in our example two other males (numbered with 2 and 3 in Fig. 3.1a); when these come nearer (Fig. 3.1b), instantly a struggle breaks out. A short period of the turmoil is shown in Fig. 3.1c, where the female with its strong mandibles can be seen; male No. 1 cannot be made out in this 'hustle and bustle', but finally emerges from the struggle as victor, as can be seen when comparing the somewhat frayed left wing and the white 'facial beard' in Fig. 3.1b, d. Further fights may follow until finally the strong female pushes away one of the males in a catapult-like manner, leaves the mating site and resumes its breeding (at first, however, the female provides itself with nectar from a flower, while at the same time possibly being harassed by smaller male 'losers').

The 'struggle arenas' in flowering plants, which like all terrestrial plants and many algae exhibit a heterophasic alternation of generations, are stigma and style on the one hand and the germination sites of the seeds on the other hand. In the

[3] The female takes over the entire brood care: collecting pollen and nectar, depositing the brood provision into a tubular brood cell made by itself from 'mortar' (in band ceramic manner), and closure of the cylindrical cup after laying a single egg. Often several such 'brood cylinders' are built next to each other and finally are 'plastered' with additional mortar to a unit.

haplophase, pollen tube competition occurs, in the diplophase seedling competition (see for example Leins & Erbar, 2008, 2010, 2018); the winners are, for example, those competitors which (genetically determined) have a faster metabolism and faster growth, respectively.

In the following, we will list some particularly appropriate systems in different designs, starting with everyday utensils and ending with ingenious 'tricks of surprise', which partly also determine human existence in everyday life.

2.1 Spreaders

The botanist and natural philosopher Raoul Heinrich Francé is often regarded as the father of bionics. The German patent he obtained in 1920 for a spreader he had constructed on the model of a poppy seed capsule was the first patent for a bionic invention (Fig. 3.2; see Francé, 1920; Henkel, 1997). The spreader was intended to enable an even distribution of the spreading material, e.g. seeds.[4] Of course, an even distribution requires appropriate handling. However, according to recent studies, under natural conditions the purpose of a capsule, as in the case of poppies and other plants, is precisely not an even distribution of seeds (and the seedlings that develop

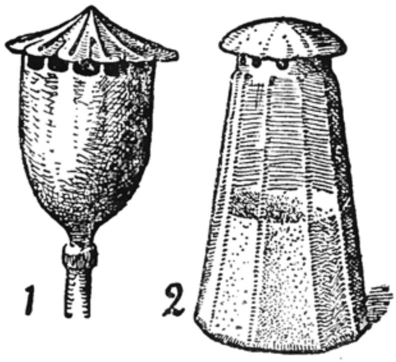

Fig. 3.2 First bionic (biotechnical) patent for a spreader by Raoul Heinrich Francé. After an even distribution of the spreading material with several models was unsuccessful ('An ordinary salt barrel, such as stands on every host table. A powder shaker …, an atomizer …'), Francé took the poppy seed capsule as a template. (From Francé, 1920)

[4] Francé did not have in mind to construct a perfect salt shaker. If he had intended to do that, the poppy capsule would not be a good model: You want your salt at the point where you aim for, e.g. on your breakfast egg and not spread evenly over your table. See Fig. 3.7.

from them, respectively) but follows the requirements of increased intraspecific competition, resulting from the accumulation of seeds near the mother plant (Fig. 3.3; e.g. Leins & Erbar, 2008, 2010; Erbar & Leins, 2018). In order to explain this accumulation, we will compare two of the many different forms of pore capsules in the poppies (Fig. 3.4), namely the capsules of the corn poppy and the long pricklyhead poppy (*Papaver rhoeas* and *Papaver argemone* ssp. *argemone*), in wind tunnel experiments (Fig. 3.5) and by field observations. The corn poppy has broad capsules with large pores, while the long pricklyhead poppy has slender capsules with small pores. It is just to demand that under equal wind conditions broad and short capsules with relatively large pores will release more seeds per time unit than long and slender capsules with relatively small pores or even with pores intersected by teeth.

The two graphs in Fig. 3.5 illustrate the expected differing behaviour. In the wind tunnel experiment, *Papaver rhoeas* releases more than 70% of all the seeds from its capsule during the first 25 gusts applied at a wind velocity of 12 m/s. In the case of *Papaver argemone* ssp. *argemone*, it is only slightly over 30%. After another 25 gusts, only about 10% of the seeds of *Papaver rhoeas* remain in the capsule, of which hardly any are dispersed by further gusts under the given experiment conditions. In contrast, the experiment in *Papaver argemone* ssp. *argemone* only comes to an end after about 175 gusts. Even then, about half of the seeds remain in the capsule. It can be concluded that more seeds only leave the capsule at higher wind velocities and then of course, lifted by the wind, get dispersed over a greater distance. Thus, differences in the spatial distribution pattern would be expected in the mentioned examples. However, it can be observed in field experiments that in *Papaver argemone* ssp. *argemone* the seeds that remain in the capsule can be released by later, gradual capsule decay (Fig. 3.6), and may be deposited not far

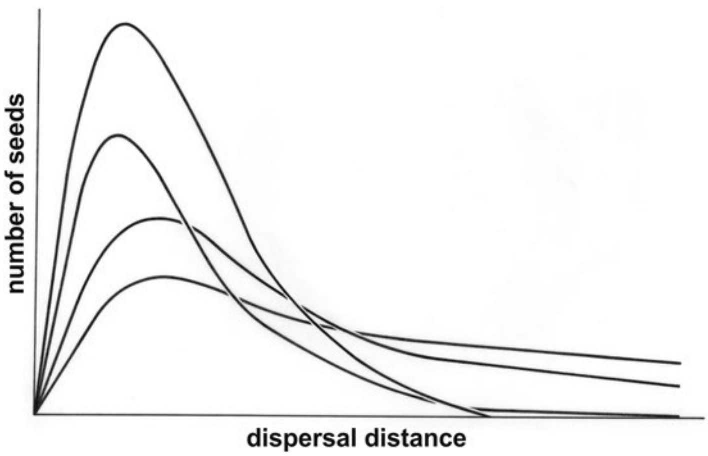

Fig. 3.3 Seed dispersal pattern (= seedling distribution pattern) exemplified in right-skewed curves. (From Leins & Erbar, 2010)

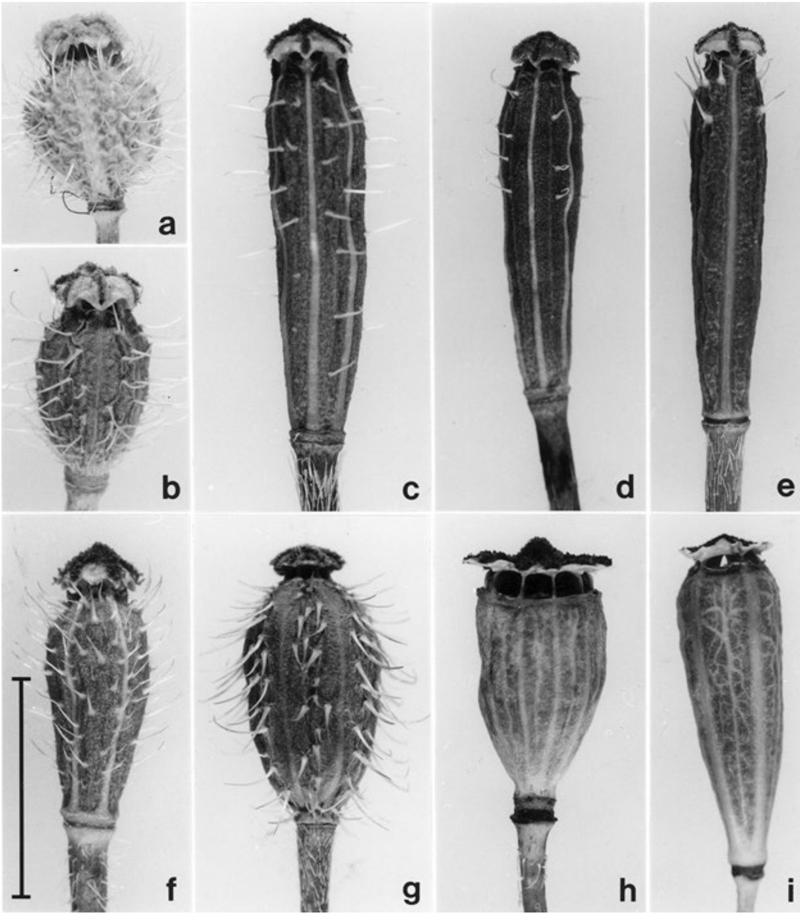

Fig. 3.4 Various capsule forms in poppies. (**a**) *Papaver pavoninum*., (**b**) *Papaver apulum*., (**c**), Papaver *argemone* ssp. *minus*., (**d**) Long pricklyhead poppy Papaver *argemone* ssp. *argemone*., (**e**) *Papaver argemone* ssp. *meiklei*., (**f**) *Papaver argemone* ssp. *nigrotinctum*., (**g**) Rough poppy *Papaver hybridum*. (**h**) Corn poppy Papaver *rhoeas*. (**i**) Long-headed poppy *Papaver dubium*. The magnification bar corresponds to 1 cm. (From Kadereit & Leins, 1988 and Leins & Erbar, 2010, respectively)

from the mother plant. The ultimately resulting dispersal pattern may then differ only slightly from that of the *Papaver rhoeas*.

As for the different temporal course of the seed dispersal, the fast emptying of the capsules due to large pores in the corn poppy *Papaver rhoeas* may be explained by the fact that a large proportion of the seeds escape from predation by grain-eating birds, which are able to easily open the capsules with their bills. It is interesting that the much slower release of seeds (in small portions) in *Papaver argemone* ssp. *argemone* is combined with a more robust capsule, which cannot be so easily broken up. Moreover, in a subspecies of the long pricklyhead poppy (*Papaver argemone* ssp.

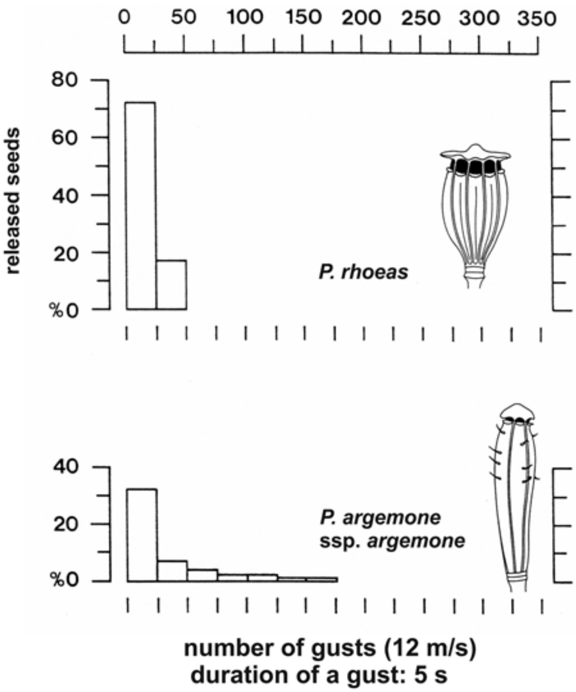

Fig. 3.5 Comparison of the temporal course of seed release in the poricidal capsules of corn poppy (*Papaver rhoeas*) and the long pricklyhead poppy (*Papaver argemone* ssp. *argemone*) in wind tunnel experiments. The stalked capsules were exposed to short (5 s) gusts of wind until no more seeds were released at a wind velocity of 12 m/s. (From Kadereit & Leins, 1988, modified, and Leins & Erbar, 2010, respectively)

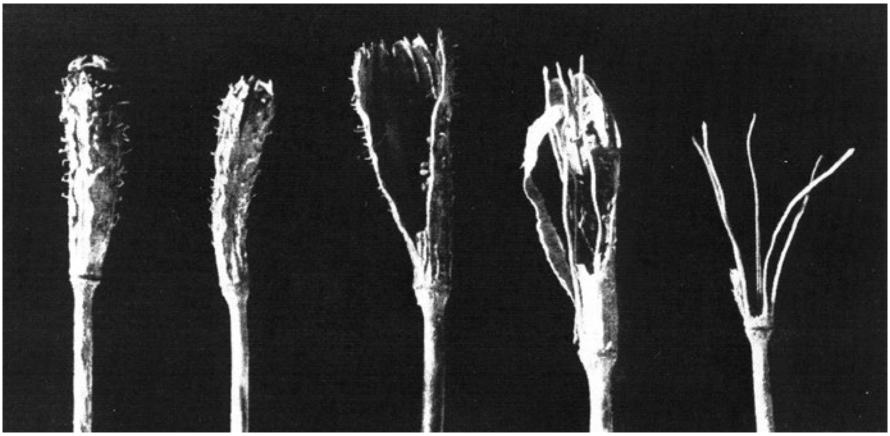

Fig. 3.6 From left to right: successive capsule decay in the long pricklyhead poppy *Papaver argemone* ssp. *argemone*. (From Blattner & Kadereit, 1991 and Leins & Erbar, 2010, respectively)

nigrotinctum), stiff bristles on the capsule surface can additionally act as shock absorbers (capsules with stiff bristles also occur in some other poppy species, Fig. 3.4).

A spatially narrowly defined competition ‘arena’ can be found in flowers, namely the stigmas above the ovaries, onto which pollinating insects transfer the pollen grains. But first, the pollen grains have to be transferred to the transporting insects. For example, in flowers of some members of the borage or forget-me-not family (Boraginaceae) with small stigmas, this is done with special pollen spreader devices. Impressive in its precision is the so-called 'Streukegel' ('pollen-shaker-box') of the borage (*Borago officinalis*, Fig. 3.7b). This 'pollen-shaker-box' is roughly comparable to a salt shaker, such as one you would want for your breakfast egg (Fig. 3.7a; see Footnote 4). The wall of the pollen container, i.e. the 'pollen-shaker-box', is formed by the five long anthers, which gradually narrow towards the tip and stand close together (Fig. 3.7c). Starting from the tip, the anthers open inwards, as can be seen from the two anthers folded outwards in Fig. 3.7d. In the two Fig. 3.7e, f, the flower is squeezed at its base between thumb and forefinger, so that all five anthers lie in one plane. The anthers are already empty, and, at this stage, their two slit-like openings extend to the base. As a whole, the folded wall parts, which surround the slits, form additional guide rails inside the spreader device, along which the pollen grains are conveyed to the tip of the anther cone. Pollen grains are only released when the anther cone is shaken. This is mostly done by honey bees (*Apis mellifera*), which always behave in the same way when visiting flowers in order to reach the nectar at the base of the flower with their mouthparts. There is a set of very well-coordinated features that together guarantee an optimal pollination process; in floral ecology, this is referred to as a pollination syndrome.

In the borage, this includes the nodding position of the flower, which places the 'pollen-shaker-box' in its functional position; the opening of the anther cone is directed downwards. The bee—while hanging on the flower—holds on to the base of the 'pollen-shaker-box' and there touches so-called coronal scales or faucal scales—spur-like infoldings projecting towards the centre of the flower, characteristic of some members of the Boraginaceae—as well as awl-like appendages of the very short filaments of the stamens, alternating with the faucal scales. Touching these appendages and inserting the proboscis between the stamens triggers a vibration[5] of the 'pollen-shaker', and pollen trickles fairly accurate onto the ventral side of the abdomen of the bee hanging on the flower (arrow in Fig. 3.7g).

If the flowers are approached several times, the bees may also 'scoop' pollen into their pollen baskets (Fig. 3.7h; arrow points to white pollen grains on the bee's hind leg). Once the 'pollen-shaker-box' has emptied, the style with the stigma becoming receptive, the landing site of the pollen grains, begins to elongate until the stigma protrudes from the opening of the 'pollen-shaker-box' (Fig. 3.7i). The same

[5] When in hanging flowers the pollen grains trickle down from a 'shaker-box' as soon as an insect touches the latter with its proboscis or head, such pollen release mechanisms are often somewhat inaccurately summarized under the term 'buzz pollination'. This term, however, describes in a stricter sense such cases in which the pollinator causes the release of pollen from cones of poricidal anthers (e.g. in *Solanum*-type flowers such as bittersweet, tomato or potato) by rapid vibrations, which produce a sound (= 'buzz'), of their thoracic muscles in a certain frequency (e.g. Michener, 1962; Buchmann, 1983; De Luca & Vallejo-Marín, 2013; Vallejo-Marín, 2019). Diverse bee taxa, in particular bumble bees, are involved in buzz or vibration pollination. On flowers of borage, bumble bees show typical buzzing behaviour (Corbet et al., 1988). Honey-bees (*Apis mellifera*), however, are not able to buzz (King & Buchmann, 2003).

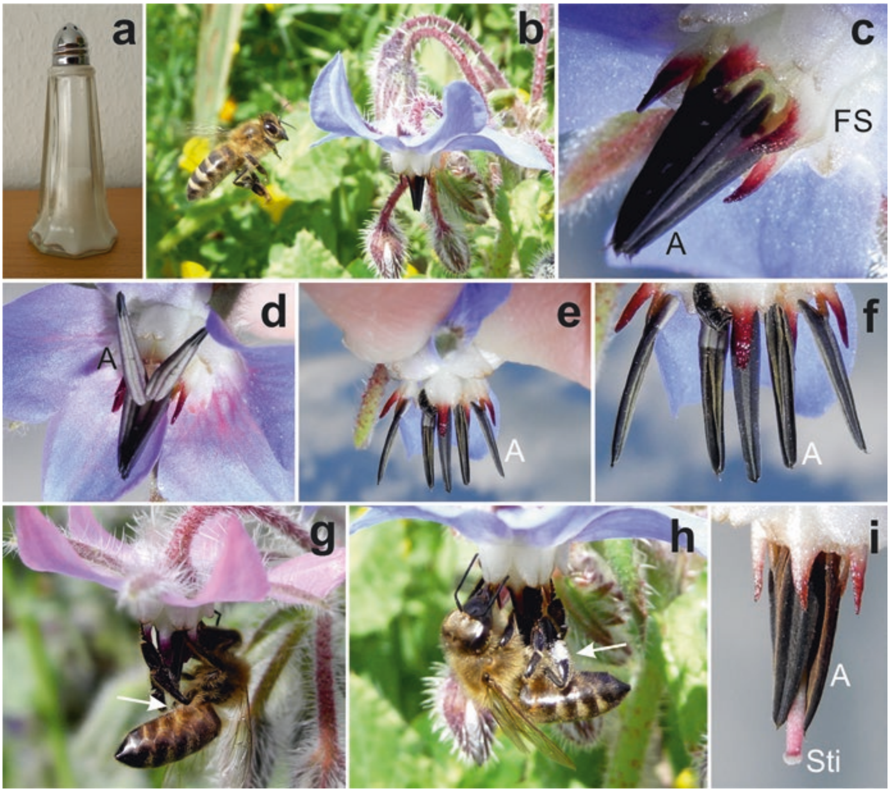

Fig. 3.7 A desirable salt shaker for the breakfast egg (**a**) finds a parallel in the 'pollen-shaker-box' of the borage flower (*Borago officinalis*; **b**–**i**). *A* anther (anther), *Sti* stigma, *FS* faucal scale, the arrow in (**g**) points to pollen grains trickling out on the ventral side of the bee, the arrow in (**h**) points to white pollen grains on the hind leg of the bee; see text for further explanation. (Image credit: Own photographs)

behaviour of insects in flowers in the subsequent female phase of anthesis guarantees precise contact of the receptive stigma with the pollinator's body site onto which pollen was delivered in the male phase of anthesis. Proterandry (i.e. male phase of anthesis precedes the female phase) is also part of the respective floral syndrome.

2.2 Attachment Methods: Suckers, Adhesive Surfaces, Hook-and-Loop Fasteners

Let's remember the 'Magdeburg hemispheres', one of the most impressive stories from the seventeenth century. With this, the engineer and physicist Otto von Guericke proved in a spectacular experiment (teams of horses could not separate two halves of a sphere inside of which a vacuum was created) that air exerts a pressure on a cavity under vacuum. The suckers of squids also work according to this principle (Fig. 3.8a). In technology, it is exploited with plastic vacuum hooks—widely used in the household (Fig. 3.8b, c). Adhesion to wall surfaces that are as smooth and clean as possible depends on the diameter of the adhesive disc.

Application of glue gives the base surfaces of the hooks much better adhesion. However, the disadvantage is that they are difficult to replace. For a comparison with an adhesive disc found in nature, we can refer to the genus *Parthenocissus*.[6] This member of the grape family (Vitaceae), which can be found, e.g. on house facades (Fig. 3.9a, b), forms small adhesive pads (Fig. 3.9c–e) at the ends of the axes of branched 'tendrils'. Their inner side, i.e. the side adjacent to a support surface, e.g. the wall of a building, becomes slimy and when drying out glues the adhesive pad to the support. The rougher the support surface—e.g. the plaster on a house facade—the more firmly the pad is bonded to it. The slimy cells can, in fact,

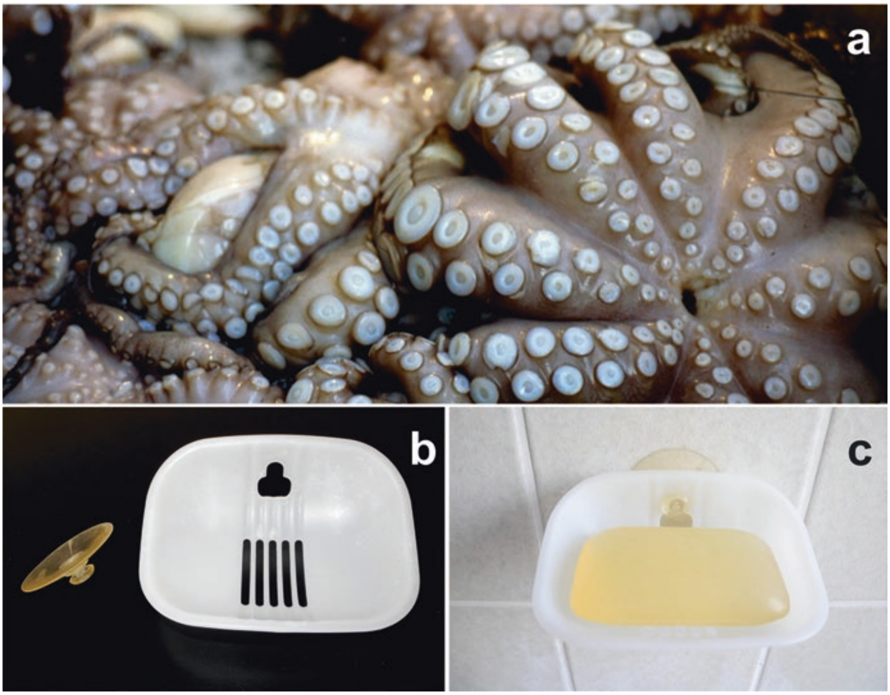

Fig. 3.8 (**a**–**c**) Natural and engineered suckers. (Image credit: Own photographs)

[6] As it seems to us, the three species *Parthenocissus tricuspidata* (native to East Asia), *P. quinquefolia* (native to North America) and *P. inserta* (native to North America) planted in Central Europe cannot be clearly separated from each other (probably cultivated varieties).

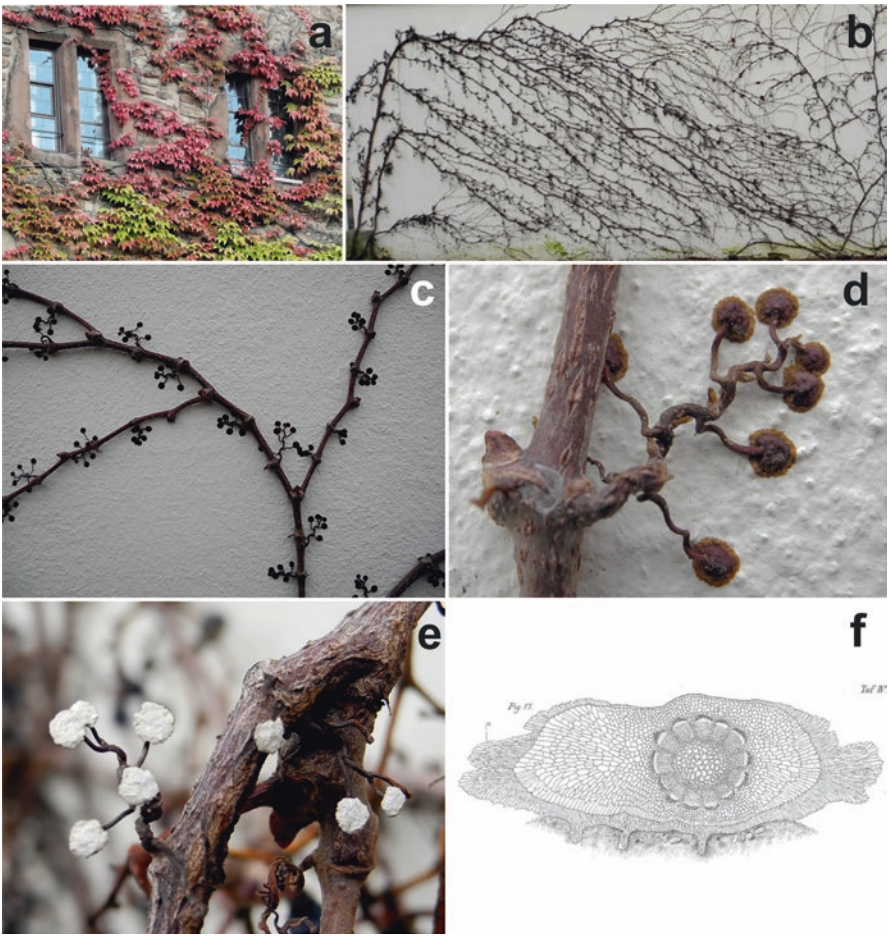

Fig. 3.9 *Parthenocissus*, a climbing woody plant that clings to house walls by means of adhesive pads, is a member of the grape family (Vitaceae). (**a**) Beginning reddening of the foliage at the Tiefburg (Heidelberg-Handschuhsheim). (**b**) Foliage-free 'climbing structure' on a plastered rough wall surface. (**c**, **d**) Adhesive pads at the ends of small branches firmly connecting the 'climbing structure' to the support surface. (**e**) Adhesive pads removed from the support surface with plaster residue. (**f**) Cross-section through an adhesion pad of *Ampelopsis muralis* (synonym of *Parthenocissus quinquefolia*) with a small piece of the support surface (Fig. 17 from von Lengerken, 1885b) (**a**: denotes the epidermis of the adhesion pad, which proliferates at the point of contact with the support surface by multiple divisions). (Image credit **a**–**e**: own photographs)

grow into fine fissures, as can be seen from a doctoral thesis as early as the end of the nineteenth century (von Lengerken, 1885a; more recent work assumes a secretion of an adhesive,[7] e.g. Steinbrecher et al., 2011).

[7] Preliminary results are available that it is a composite adhesive of polysaccharides, callose and mucilaginous pectins (Bowling & Vaughn, 2008).

This can cause problems when removing the climbing shrub because typically whole pieces of the climbing substrate are torn off. However, another climbing shrub, common ivy, causes even more problems during removal (Fig. 3.10a–c).

Common ivy (*Hedera helix*) of the ginseng family (Araliaceae) is the only root climber native to our region. Root climbers can develop attachment roots along their shoots, with which they attach themselves firmly to trees or rocks (Fig. 3.10d–f). In doing so, the roots do not penetrate into the vascular bundle of trunks and branches (thus ivy is not a parasite!). But how does ivy manage to grow even on vertical walls without slipping? The reason for the permanent hold lies in the ivy's root hairs. These are located behind the root tip and usually serve to absorb water and dissolved mineral salts. In ivy, however, a change in function has taken place.

On the surface of the small, unicellular root hairs (they have a diameter of 10–15 μm and a length of 20–400 μm) sit excrescences that contain a sticky liquid (Fig. 3.10g). When they come into contact with a tree bark or a house wall, they burst open and the liquid hardens immediately (Fig. 3.10h). Because this process is very rapid, the chemical composition of the liquid has not yet been elucidated. However, another aspect of the attachment process could be traced. When the root hair dries out in a depression in the bark of a tree or house plaster, no matter how small, it twists during this process and thus becomes shorter.

The twisting is based on thin cellulose fibres (so-called micro-fibrils), which run at an almost constant angle spiralling around the longitudinal direction for most of the root hairs. The angle between the main longitudinal axis of the root hair and the cellulose micro-fibrils is approximately 40°. However, the micro-fibril angle increases abruptly at the tip of the hair (it is approx. 55°), and thus the hair tip curves like a spoon or hook, providing a further anchoring within the cavities of the substrate. In addition, the ongoing shortening of the attached root hairs during the drying process pulls the entire ivy shoot closer to the tree bark or building wall. All these fascinating, altogether intelligent findings are due to the subtle investigations of Melzer et al. (2010; University of Freiburg and Karlsruhe Institute of Technology—KIT; see also Speck, 2011). Now it is no longer surprising that the ivy plant usually cannot be removed from a building wall without damaging the plaster. The ivy principle does not work on absolutely smooth surfaces such as glass or aluminium. But with surfaces that have at least microscopically small cracks or depressions, the ivy adhesive roots create an optimal, permanent bond thanks to their special sticking and hooking-in adhesion system.

Attach–detach–attach–detach or close–open–close–open: The hook-and-loop fasteners (often referred to by the genericized trademark Velcro fastener)! It is one of the often cited achievements of bionics. This bionic product has experienced a veritable and triumphant success and is indispensable in the fashion and textile industry, for example. The Velcro fastener was invented by the Swiss engineer George de Mestral, who patented it in 1951. The model for his invention was the compact inflorescence and infructescence, respectively, of a members of the composites (Compositae = Asteraceae), namely the flower head of the burdock (*Arctium*, e.g. *Arctium lappa*; Fig. 3.11a, b). In the burdock, the inflorescence (= head = capitulum) is surrounded by an envelope consisting of numerous bracts (= involucrum),

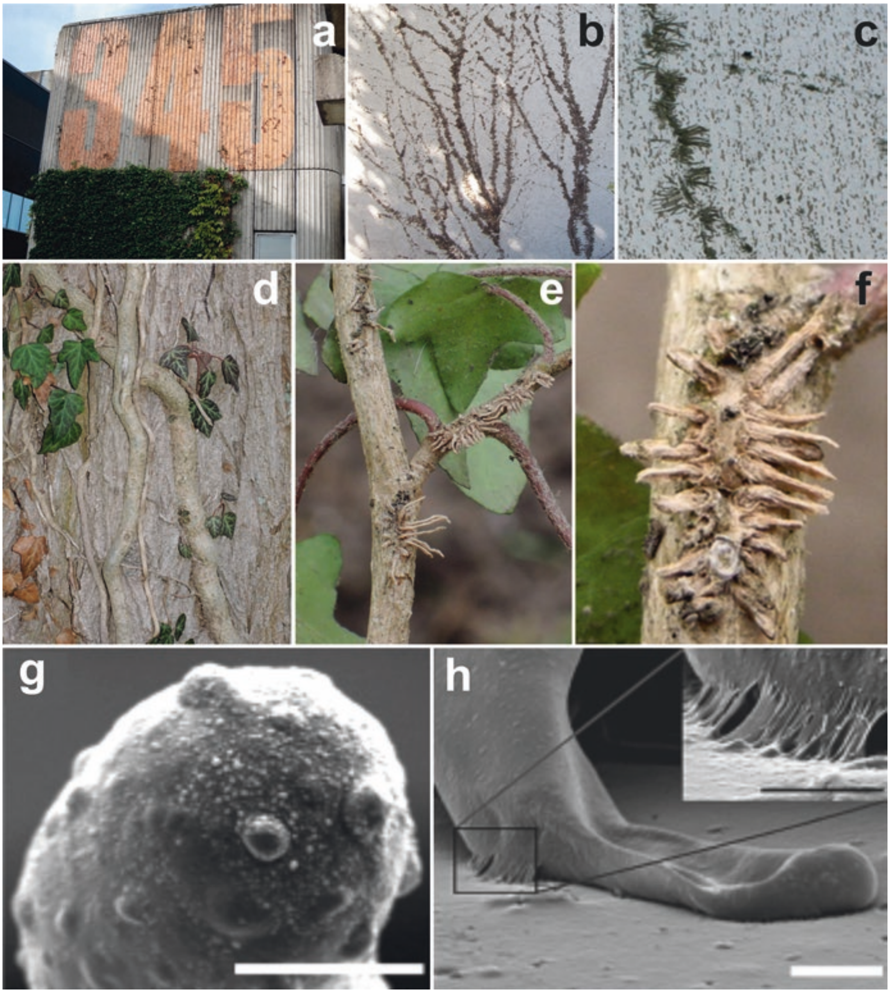

Fig. 3.10 Common ivy *Hedera helix*. (**a**–**c**) Adherent root remnants after removal of the plant by force from a concrete wall in the building complex 'Theoretikum', Heidelberg University. (**d**) Common ivy plant climbing a tree. (**e**, **f**) Shoot-borne adhesive roots of ivy plants. (**g**, **h**) Scanning electron micrographs of root hairs (from Melzer et al., 2010). (**g**) Tip of a root hair with spherical excrescences that burst on contact and release an immediately hardening liquid, the glue. (**h**) Root hair attached to a polyester film (Mylar film). The inlay image shows strands of glue that adhere the root hair to the substrate. (Image credit **a**–**f**: Own photographs)

as is common in the Compositae. In the case of the milk thistle or cardus marianus (*Silybum marianum*), the bracts are voluminous and bizarre, in the case of the daisy (*Bellis perennis*) they are narrow and unremarkable, and in the case of the artichoke (*Cynara cardunculus*) we enjoy its fleshy basal part dipped in a sauce. In *Arctium*, the numerous narrow involucral bracts possess sharp, upwards bent fine hooks at their tips (Fig. 3.11a, b). These burrs can get entangled in the hair coat of passing

Fig. 3.11 Hook-and-loop fastener (Velcro fastener): model and imitation. (**a**, **b**) Inflorescences and infructescences of the greater burdock *Arctium lappa*. (**c**) Shoe with Velcro fastener. *H* hook layer, *L* loop layer (fine threads). (**d**) Hooks. (**e**) Curled threads (loops). (**f**) Closure of both layers in section. (Image credit: Own photographs)

mammals (e.g. hares or deer) and are either torn off and carried away by the animals[8] or, if the burrs cannot be torn off the plant, the animals trigger a catapult effect so that the individual fruits are ejected from the fruiting head(s). The burrs, the almost globular involucral containers, thus serve as first order diaspore[9] for the dispersal of the fruits (nuts), which are enclosed in the container and can easily fall out of it as second order diaspores. In terms of the bionic product, attachment and removal of objects require elastic, yet relatively stable hooks on one surface and wavy, thin hairs on the other, the latter effectively acting as loops (Fig. 3.11d–f).

---

[8] For de Mestral, the burrs in the fur of his dogs provided the template for the hook-and-loop fastener.

[9] The term 'diaspore' refers to dispersal or propagation units (see e.g. Leins & Erbar, 2010; Erbar & Leins, 2018).

2.3 Scratch-Resistant Surfaces

Here we are concerned with surfaces that do not get scratched when subjected to mechanical stress, for example, by sharp particles such as sand or abrasive objects. To learn about different ways of solving this problem in plants, we go to the dune regions of seashores, for example. Owing to the frequently blowing wind, sand blowers are to be expected in these surroundings. In technology, suitable solutions could be achieved, for example, by hardened steel with a smooth surface or by certain paintworks. In plants it must be sufficient that their outer layer synthesized by epidermal cells, the so-called cuticle,[10] has a smooth surface of a certain hardness and thickness. The leaves of the plant protected in this way are hard and leathery tough; impressive examples can be found, for example, in sea holly or seaside eryngo *Eryngium maritimum* (Apiaceae, Fig. 3.12a, b) and in seashore false bindweed *Calystegia soldanella* (Convolvulaceae, Fig. 3.12c).

Somewhat unusual in plants—but quite frequently used in technology—is a defence against damage with the aid of the damaging material itself, namely the roofing-paper effect. An example is *Silene succulenta* (carnation family, Caryophyllaceae), a succulent perennial herb from the coastal sands of the Mediterranean (Fig. 3.12d). The sand brought by the wind sticks to the sticky surface of the plant and quasi slows down further grains of sand that hit it.[11]

Even more surprising is the strategy of a butterbur species occurring on sandy areas, namely *Petasites spurius* (Asteraceae, Fig. 3.12e). Butterbur species are characterized by relatively large leaf blades. In outline, the leaves of the relevant dune butterbur (= tomentose butterbur) are broadly cordate with elongated lateral lobes, so that the leaf blade is broader than long. The relatively thin and easily movable petiole is attached to a broadly triangular base of the blade. The upper side of the leaf blade is dark green, the underside white due to a dense tomentose pubescence (hairs dead and air-filled). In still air, the leaf blade is more or less spread out and photosynthesis can be fully active. If a stronger wind comes up, it causes the easily movable lateral lobes of the leaf blades to turn inwards and thus, together with the remaining part, form a conical bag (Fig. 3.12e), which then, with the help of the easily movable petiole, moves into the appropriate position determined by the wind direction: Tip of bag towards windward, opening of bag towards leeward. This causes the sand to bounce against the protective hair cover. The ingenious thing about this is that the protective action taken is only temporary (in calm weather, photosynthesis can be fully restarted). One could now think about a possible technical transfer. However, this should only be a suggestion at this point.

[10] The main component of the cuticle is cutin. Similar to the suberin (component of cork), which replaces cutin in secondary dermal tissues (periderm), i.e. the barks in woody plants, it is a lipophilic copolymer. It forms the matrix for waxes embedded in the cuticle.

[11] Like the sanded roofing paper, the sanding also protects against solar radiation; the sand chips reflect the sun's rays and, in this way, prevent excessive heating on sunny days.

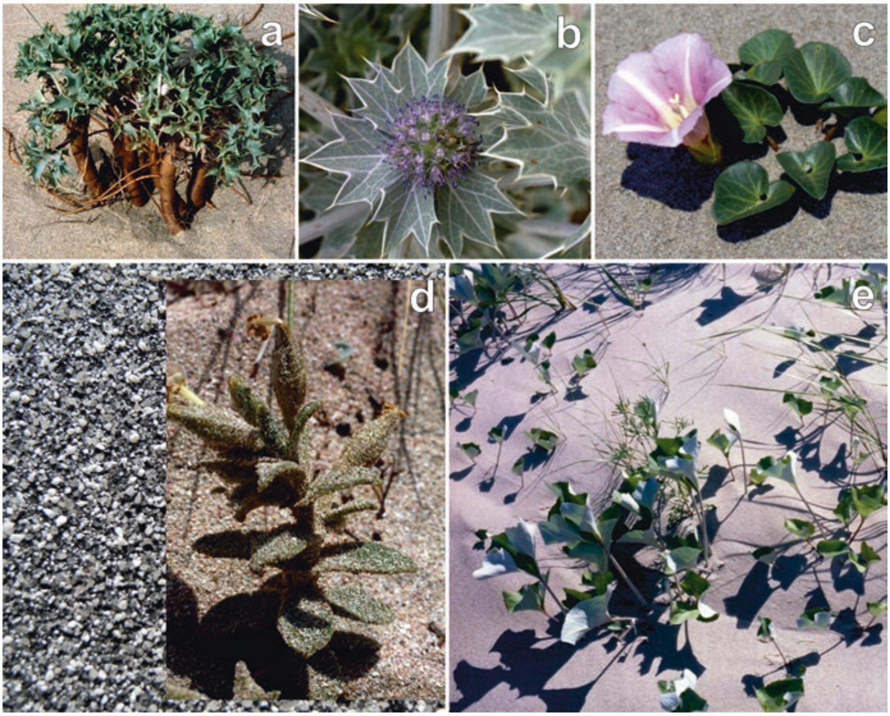

Fig. 3.12 Leaf surfaces. (**a**, **b**) Sea holly or seaside eryngo *Eryngium maritimum*. (**c**) Seashore false bindweed *Calystegia soldanella*. (**d**) *Silene succulenta* with thick leaves covered with sand; image mounted on roofing paper. (**e**) Dune (= tomentose) butterbur *Petasites spurius*. See text for explanations. (Image credit: Own photographs)

2.4 Corrugated Surfaces as Protection Against Cold and Heat: The Seersucker Effect

There are different ways of overwintering in flowering plants: Either—and this is the case in the so-called annuals—they get through the winter only with the help of their seed production, or they overwinter additionally with underground organs (rhizomes, tubers, shoot or root thickenings by cambium activity [secondary meristem]) or as wintergreen rosette plants, where the air-containing snow provides cold protection (this also applies to runners located directly on the ground), or they are woody plants that usually shed their leaves and leave overwintering buds in their leaf axils. As far as protecting the leaves from the cold against a frozen ground, i.e. from below, some rosette plants are interesting. A rosette plant of the Labiatae or mint family (Lamiaceae), namely the dragonmouth or Pyrenean dead-nettle *Horminum pyrenaicum* (Fig. 3.13a), which occurs in the Alps and Pyrenees and is very common in the Lake Garda region, protects its leaves, especially young leaves, which are spread flat on the ground, by means of air cushions in such a way that the tissues between the leaf veins (the so-called intercostal fields) experience increased surface growth and become convex. Something similar, by the way, can also be observed in savoy cabbage. Being a bad conductor of heat, air under the underside of the leaf protects the leaf from freezing to death.

The *Horminum* leaf can also be used as a model for a certain type of crepe weave in fashion or even in the manufacture of bed linen, but with the opposite effect, namely thermal protection. It is the so-called seersucker fabric (the word comes from Persian and means milk and sugar). These fabrics are excellent for a comfortable skin climate. Shirts made of this type of weave (during the weaving process, the warp threads running lengthwise are alternately stretched looser and tighter) are quite pleasant to wear on hot summer days, since this feature causes the fabric to be mostly held away from the skin when worn (it only comes into contact with skin

Fig. 3.13 Surfaces. (**a**) Centre of leaf rosette of dragonmouth *Horminum pyrenaicum* (Lamiaceae) with rugose leaves. (**b**) Duvet cover in the seersucker weave (crepe weave with a three-dimensional 'wrinkled' surface effect). (Image credit: Own photographs)

quite loosely at certain points), facilitating heat dissipation and air circulation. In the case of the duvet covers (Fig. 3.13b), which enable a pleasant sleep in summer and winter, there is another advantage that should not be underestimated: seersucker bed linen must not be ironed; it also looks quite good in its ‘crumple look’.

2.5 Mechanically Stable Constructions of Larger Size: Folded Structures, Lightweight Construction, Floatability

In connection with a mechanically stable surface, three-dimensional constructions are sought, which are characterised by high stability even under maximum load. Stressing factors can again be the wind, but also water, weights, volume changes and earth tremors. Looking for plants as models for a corresponding technical solution, we go to the respective areas on our planet where extremes naturally prevail in this respect. In Florida, for example, hurricanes occur regularly, to which the palms are excellently adapted with their plicate leaves clustered in a terminal crown (Fig. 3.14a, b). Nevertheless, such adaptation in the folding of the leaf blades has its limits; occasionally we come across the corpses of palm trees without their crown of leaves (Fig. 3.14c).

Palm trees that have ‘strayed’ on rocky coasts run the additional risk of being hit by powerful waves (Fig. 3.14d). The folding structure of their leaves again contributes significantly to their survival. The authors of this article are always impressed by the severely affected specimens of the dwarf palm (*Chamaerops humilis*), the only palm species in the Mediterranean region, if one disregards the Cretan date palm *Phoenix theophrasti*,[12] which is only distributed in small areas. The areal of *Chamaerops humilis* covers the western and central Mediterranean; in Sicily it is found in several seaside locations, where it is dominant in so-called dwarf palm garrigues (Fig. 3.14d). Its leaf blades are fan-like dissected (Fig. 3.14e). However, this is not a true pinnation, which ontogenetically is due to marginal meristem fractionation (Fig. 3.3 in Leins & Erbar, 2017). In contrast, it is due to a very late tearing of the leaf blade as it unfolds.[13] As illustrated in the charts (Fig. 3.14g, h), necrotic narrow strips are formed, on every second edge[14] of the fold structure, which in many cases can be seen as drooping threads in tropical palm species (Fig. 3.14f). In the dwarf palm, the narrow necrotic areas at the edges are visible as whitish stripes (total reflection of light on the air-filled dead tissue strips; Fig. 3.14i, k). The early folding of the palm leaves and the extremely dense arrangement of folds allows a completely uncomplicated enlargement of the area if the growth is regular

[12] *Phoenix theophrasti* occurs only in a few locations on Crete and on the southwest coast of Turkey.

[13] In addition to the fan shape (fan palms), there is the pinnate shape (pinnate or feather palm, e.g. date palm, *Phoenix*), which is also due to tearing. The latter is less stable in wind.

[14] In *Chamaerops humilis,* additional dividing stripes appear from the periphery of the leaf at each edge.

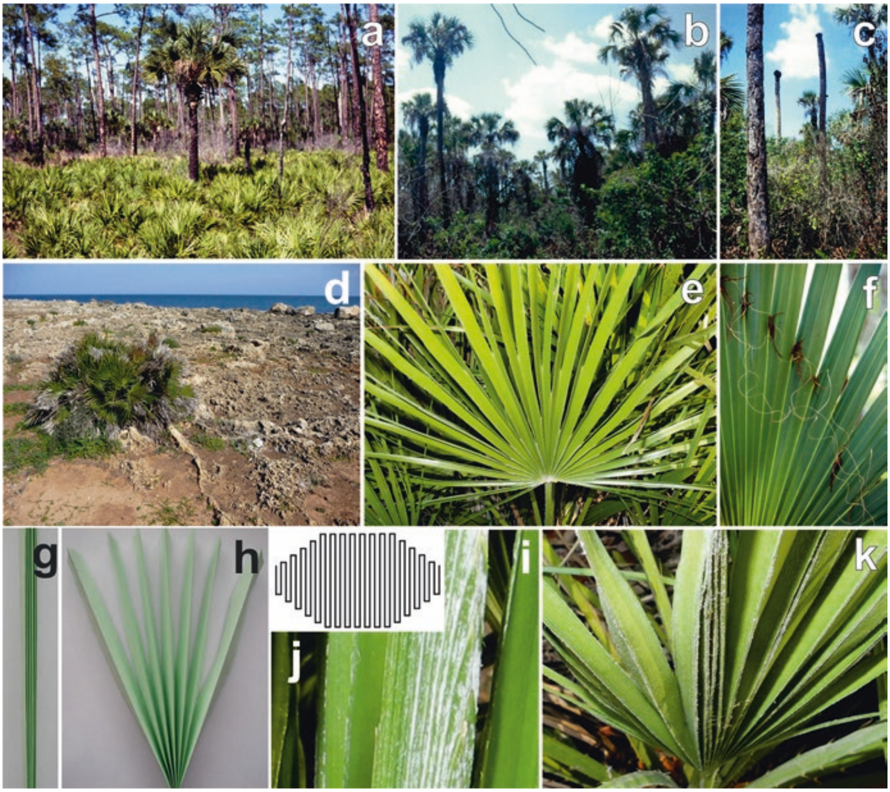

Fig. 3.14 Fold structures in palm leaves. (**a**–**c**) Various palms of Florida. (**a**) In the background: cabbage palmetto *Sabal palmetto*, in the foreground (creeping): saw palmetto *Serenoa repens*. (**b**, **c**) Royal palm *Roystonia regia*. This palm has the ability to easily release their leaves in too strong winds, a supposed adaption serving to prevent toppling. If the growing bud, the 'palm heart' or shoot apical meristem is intact, the typical leaves will sprout within a few years. (**d**, **e**, **i**–**k**) Mediterranean dwarf palm (*Chamaerops humilis*). (**d**) Site on the rocky coast of south-eastern Sicily (Riserva naturale orientata Oasi faunistica di Vendicari). (**e**) Fan-shaped leaf blade. (**i**) A closely plicate young leaf blade with schematized transverse section (**j**). (**k**) Leaf in the process of unfolding. (**f**) Detail of a fan leaf of a tropical palm species (Thailand) with necrosis threads between the fan segments. (**g**, **h**) Paper model of a fan leaf unfolding. (Image credit: Own photographs)

(Fig. 3.14j). The edge formation in a tough-elastic system requires a constant evasion from a force effect, e.g. wind, which becomes noticeable in a lurching of the leaf segments and the entire leaf, respectively.

The fact that a load pressure acting perpendicularly on a free-standing fold structure can be substantially increased compared to a flat surface is shown by a simple experiment: Place a sheet of paper on a bowl and deposit table salt onto it; even a small amount causes deformation. If the same sheet of paper is folded, it will withstand a multiple load before it gets out of shape (cf. Fig. 3.15a–d). Folded structures work very well as stabilizers in bridges (Fig. 3.15e). But just think of packaging cartons made of corrugated cardboard. It is not just a matter of reducing weight, but for the same size, a box made of double wall cardboard has a significantly higher load-bearing capacity than one made of single wall cardboard (30 kg and 20 kg, respectively).

If an evenly folded surface is closed to form a cylinder (Fig. 3.15f), we obtain the outline of a ribbed cactus (Fig. 3.15g, h). In the succulent cactus family (Cactaceae), members of the columnar form are fluted with strong ribs and corresponding furrows that extend from base to stem apex. One of the two tallest ribbed cacti is the saguaro *Carnegiea gigantea*, native to the southwestern USA and Mexico[15] and made famous by many 'Western movies.' A fully grown saguaro (at 10–12 m height and weighing 6–8 tons) is said to have in its trunk a water reservoir of 2000–3000 (Walter, 1973) or even 4000 L (Pfadenhauer & Klötzli, 2014). After an extensive thundershower it can absorb up to 750 L of water (Mabberley, 2008). During a long dry period, it can lose this amount of water through transpiration—thus a constantly repetitive change of internal volume. This takes place without any tension in the surface. Indeed, the surface remains the same whether the ribs approach each other and become narrower (during drought) or move away from each other and gain width (during water uptake; Fig. 3.15k). This is called the bellows or accordion effect. Filling—emptying of the water storage tissue in columnar cacti is thus not like filling a balloon (where the circumference increases but at the same time the wall becomes thinner, to the point of rupture and complete structural destruction). In fact, the increasing turgor force is simply accommodated by changing the geometrical configuration of the rib cross section. Bellows and accordion are certainly not copied from the cacti, which occur only in America. To boost a fire, the bellows was invented several times in parallel by humans early on, without knowledge of the water-household of the cacti at that time.

Stabilization of lightweight constructions is often found in floating objects. Spectacular in this respect are the two giant water lily species *Victoria amazonica* and *V. cruziana* from the waterlily family (Nymphaeaceae). Their huge circular leaf blades with erect margins (Fig. 3.16a) and a submerged petiole in the middle (Fig. 3.16b, c) can be up to 3 m in diameter. They are native to tropical South America. The plants are often cultivated in Botanical Gardens, and one can sometimes see children lying, sitting or standing on the floating leaf blades on postcards and pictures on the Internet to demonstrate their stability despite relatively sparse construction material. Out of the water, however, the stability of the leaf construction is at an end. The construction properties are all about adapting to the buoyancy of the water. Their fragility in the air is noticeable in the form of folds and, in some cases, cracks (Fig. 3.16b).

We quickly become aware of the adaptation in detail when we study the morphology and anatomy of the waterlily leaf. On the blade underside, radial ridges, which are spiny like the petiole itself, radiate from the point of attachment of the

[15] Equally tall, or even somewhat taller, is the cardón (*Pachycereus pringlei*) with a similar distribution area (but the two cactus species never occur side by side).

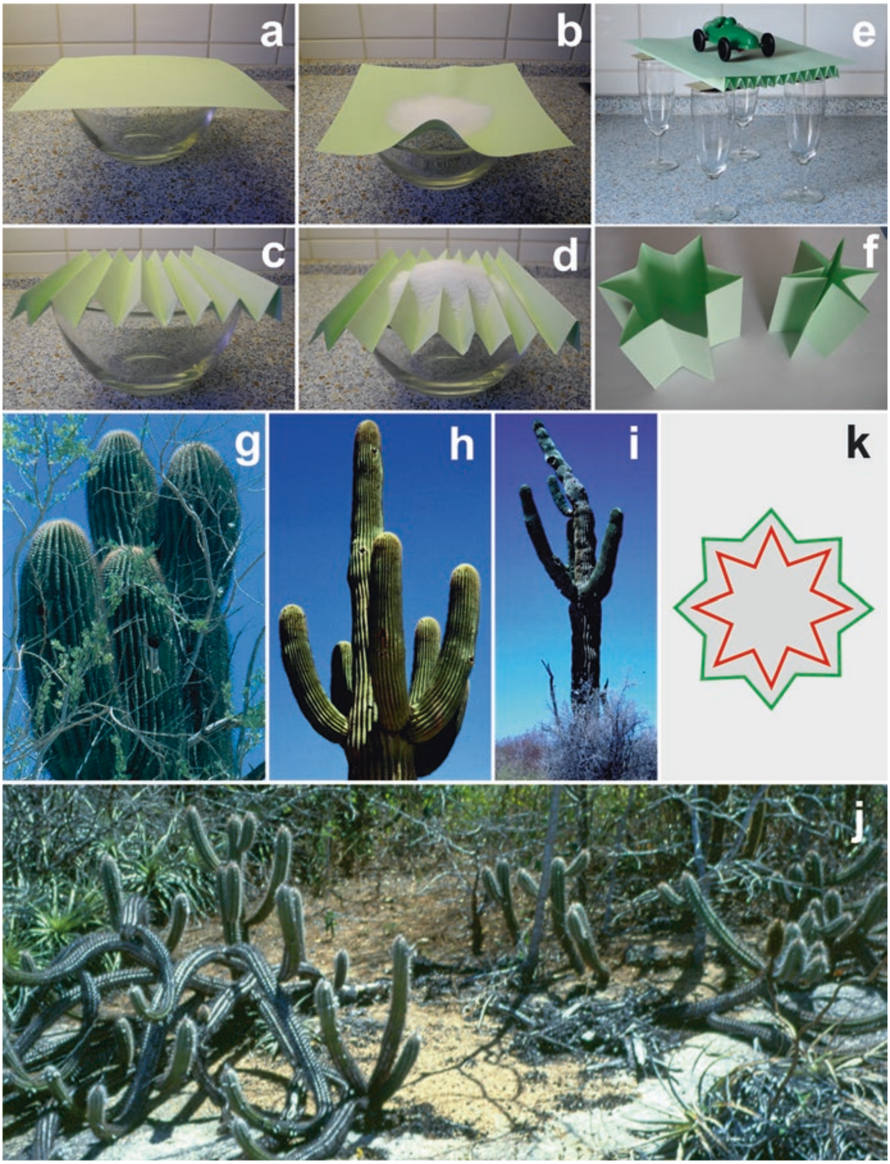

Fig. 3.15 Stability of folded structures. (**a**) Unfolded sheet of paper loaded with salt deforms even at a small load (**b**). (**c**, **d**) The same sheet of paper folded uniformly deforms only at a multiple load. (**e**) Folded structures as stabilizers in bridges. (**f**) Folded structure closed into a cylinder (star-shaped in cross-section) causes bellows or accordion effect. (**g**–**i**) Saguaros (*Carnegiea gigantea*) of various ages. The holes found in their stems are entrances to bird nesting cavities (of striped owl *Asio clamator* and Gila woodpecker *Melanerpes uropygialis*). Too many nests can lead to instability (**i**). (**g**) In the area of a wash (a dry river flowing intermittently after heavy rains), the 'nurse plant' (*Parkinsonia florida*, Fabaceae) still thrives near the saguaro (at drier sites, the saguaro will eventually literally undermine the water supply of its nurse plant). (**j**) *Pilosocereus gounellei* at the

petiole and branch dichotomously several times towards the periphery of the leaf blade (Fig. 3.16b, c). Within these ridges (Fig. 3.16f shows a cross-section through a ridge) run narrow vascular bundles, surrounded by an air-containing thin-walled tissue. Large air-filled cavities (intercellular spaces) form an almost regular pattern in the petiole (Fig. 3.16d). They are connected to the numerous narrow air channels (intercellular spaces) of the radial ridges, as can be seen from a section at the 'distribution point' of the petiole base (Fig. 3.16g; *BR* base of radial ridges). The radial ledges (R in Fig. 3.16e) are connected to each other by lower transverse ridges (T in Fig. 3.16e, f). The delicate rib system is able to keep the actual chlorophyll-containing tissue, the so-called mesophyll, which together with the surrounding epidermis is quite thin, stable on the water, and only on the water. The epidermis (the outermost layer of cells) of the upper side of the leaf is occupied by innumerable stomata (for gas exchange and transpiration; Fig. 3.16h).

The ability to float is ensured—this applies to plant organs or parts of organs in general—by an extensive system of air-filled cavities (intercellular spaces). Random changes at different points in the life cycle during evolution resulted in perfect (or almost perfect[16]) adaptation to swimming on water via the selection principle (natural selection). For example, water could be used as a medium (or vehicle) in seed dispersal. Consider, for example, the dispersal of the fruit of the coconut palm (*Cocos nucifera*): It obtains buoyancy by dissolving the tissues between the vascular bundles underneath a leathery outer skin (exocarp) and outside a hard stone (endocarp) surrounding the actual seed (cf. Leins & Erbar, 2010; Erbar & Leins, 2018).

In the sea daffodil *Pancratium maritimum* (Amaryllidaceae) from the coasts of the Mediterranean (Fig. 3.17a), it is not the fruits but the seeds themselves that constitute the floatable diaspores: their seed coat contain the dead air-containing cells (Fig. 3.17b, c; cf. Leins & Erbar, 2010; Erbar & Leins, 2018). Most likely this richly chambered envelope also serves as mechanical protection for the seed. If the outer air-filled cells are mechanically injured—e.g. if the seeds are driven by the wind over sandy surfaces as so-called ground-runners (an additional dispersal option)—the floating ability can be maintained without restriction. The higher the number of cavities and the stronger and tighter the partition walls (cell walls) are sealed together, the higher the safety. 'Batten down the hatches' is a phrase used in

Fig. 3.15 (continued) edge of an inselberg (in the back of the photographer) near Alagoinha (Federal State Pernambuco, NE-Brazil) with view into a dry cactus bush of a Brazilian Caatinga (thorn bush savannah). (**k**) Schematic cross-sections through a ribbed cactus; red outline: after a prolonged dry period, green outline: after a heavy thundershower in summer or a long lasting light rain in winter; the increase and decrease in volume proceed simply, in that only the distances between the outer edges of the ribs change, i.e. only the rib edge angle increases/decreases (the outline of the stiff outer skin remains the same length). (Following Spalding, 1905 and Walter & Breckle, 1984. Image credit: Own photographs)

[16] A compromise is always to be expected when a problem solution is in a 'conflict of interests', or better a conflict of goals, with further adaptations. Technology can also learn a lot from compromises.

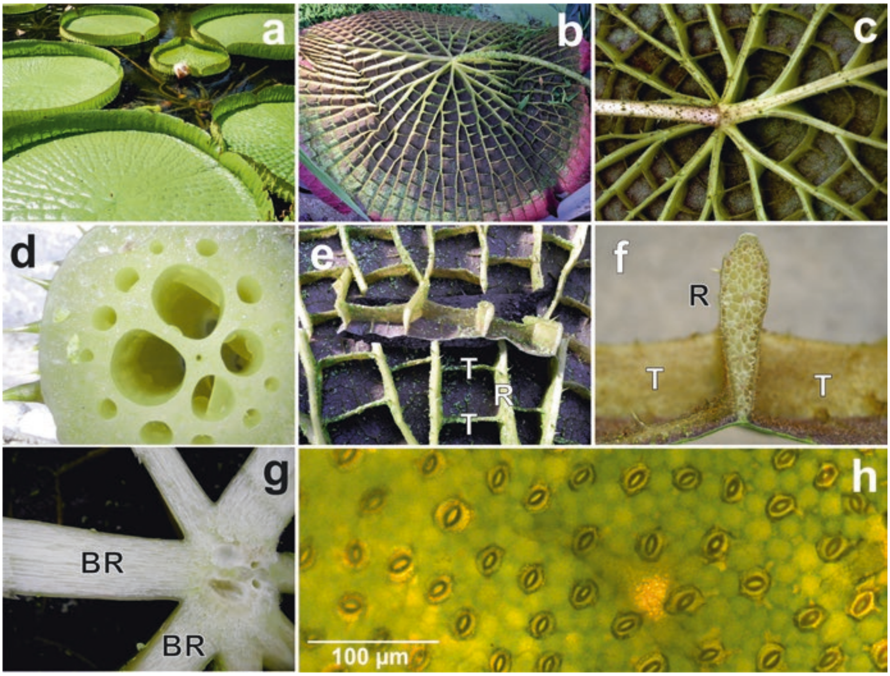

Fig. 3.16 Giant waterlily *Victoria*. (**a**) Huge, stalked floating leaf blades surrounding a flower. (**b**) Bottom side of the leaf with petiole base. (**c**) Detail showing radial ridges branching from petiole base. (**d**) Pattern of intercellular spaces in petiole. (**e**) Radial and transverse ridges. (**f**) Cross-section through a radial ridge. (**g**) Section through the 'distribution point' at the petiole base. (**h**) Epidermis of upper leaf surface with numerous stomata. *BR* base of radial bar, *R* radial bar, *T* transverse bar. (Image credit: Own photographs)

maritime shipping. In fact, the partitions in the seed coat of the sea daffodil can be compared to the bulkheads in the hull of a passenger ship. If the bulkheads are not tightly sealed by the opening of bulkhead doors, or if there are too few of them from the outset, the risk of the ship sinking after an accident is increased (see, for example, the 'Costa Concordia', Fig. 3.17d; Culjak, 2014).

2.6 Stability Aspects in the Architecture

'Solid ground underfoot'—that's not what the trees growing in the 'Wobbly Wood' ('Wackelwald', an attraction near Bad Buchau, Baden-Württemberg) have. In this woodland, under a soil layer of peat only 30 cm thick, there is a pudding-like mass of deposits about 6 m thick of a nearby, formerly larger lake, the Federsee. The adaptation to achieve a sufficient stability of the trees consists in the ability to form so-called buttress roots, strong, almost horizontal, board-like roots at the base of the trunk due to one-sided secondary growth. This ability is genetically determined, but

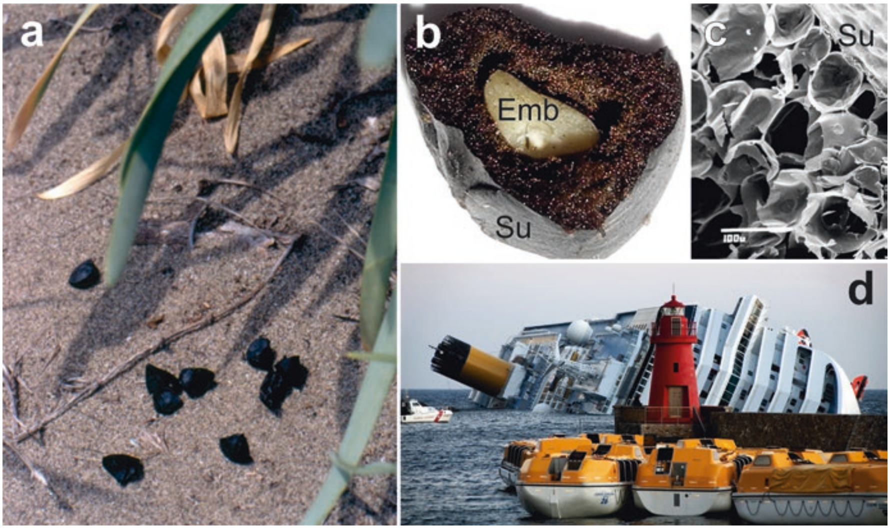

Fig. 3.17 Floating ability. (**a**–**c**) Seeds of the sea daffodil *Pancratium maritimum* (Amaryllidaceae). (**a**) Seeds released from the fruit lying on the beach near the mother plant. (**b**) Seed cut open; a thick but air-filled and thus light seed coat envelops the embryo (Emb). (**c**) Peripheral section of seed coat in scanning electron micrograph showing air-containing tissue and smooth surface (Su). (**d**) Accident of the 'Costa Concordia': The cruise ship lying aground, in the foreground some lifeboats in the harbour of Giglio. (Image credits **a**–**c**: Own photographs, **d**: Roberto Vongher, Wikimedia Commons - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=18045701)

only comes into effect when the soil is very wet. In the 'Wobbly Wood', among the trees with buttress roots, the main one to be mentioned is the moor birch *Betula pubescens* (Betulaceae; Fig. 3.18a). A wave-like swaying of the forest floor can be felt when a wind moves the trees back and forth, transmitted via their shallow root system.

Anyone standing for the first time in front of a giant tree up to 60 m high in a tropical rainforest, e.g. in Thailand (*Ficus spec*., Fig. 3.18b), is virtually overwhelmed by the mightiness of the buttress roots, which can reach up to 9 m up the trunk. The occurrence of such roots is an adaptation to the relatively thin soil layer in the tropical rainforest. The trees, in turn, are shallow rooter, whose root system usually reaches a depth of only 30 cm. The high stability due to the buttress roots running diagonally upwards is imitated in architecture, for example, in the construction of a large hotel in the earthquake hotspot San Francisco (USA; Fig. 3.18c, d). Guest rooms are located exclusively on the periphery of mutually supporting fronts and are accessed through galleries. The residential fronts leave a huge representative hall between them.

Another construction principle of an 'earthquake-proof' hotel can be found, for example, in Yokohama (Japan; Fig. 3.19e, f), imitating the excellent bending

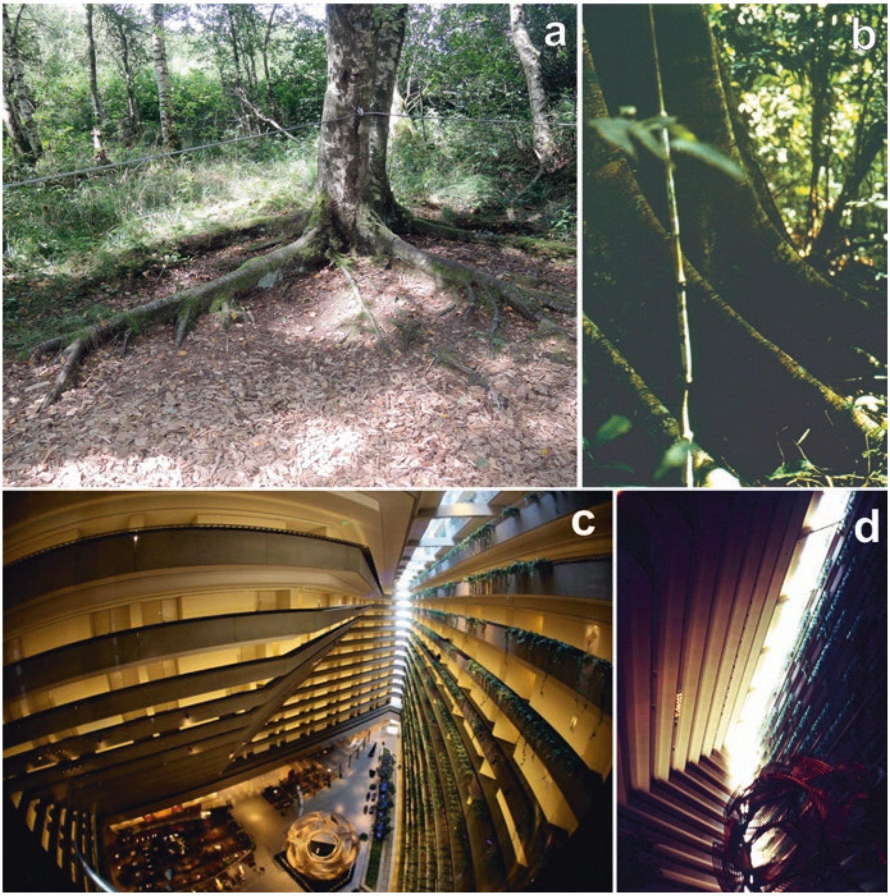

Fig. 3.18 Model buttress roots. (**a**) Trunk base with buttress roots of a moor birch *Betula pubescens* in the 'Wackelwald' ('Wobbly Wood') near Bad Buchau. (**b**) Buttress roots of a rainforest giant in the tropical rainforest in Thailand. (**c**, **d**) Imitation in the architecture: an 'earthquake-proof' hotel in San Francisco (Hyatt Regency); for details see text. (Image credits **c**: https://www.businesstraveller.de/hotel/hippe-hallen-die-zehn-spektakulaerstenhotel-lobbys-der-welt/; **a**, **b**, **d**: Own photographs)

strength of grass blades, namely bamboo (Fig. 3.19a–d).[17] The living space occupies the wall of a huge hollow cylinder (the rooms are correspondingly small!). Individual diaphragms, corresponding to the axial part of a grass node (at this point the leaves arise), prevent kinks when bending, thus increasing the bending strength. Whether and in what number such partitions are present in the hotel in question is beyond our knowledge. At the very top there is a restaurant, which is also built in a ring shape (Fig. 3.19f).

[17] We were able to convince ourselves of the bending strength in the restaurant on the 40th floor, when during a violent typhoon the building began to sway noticeably.

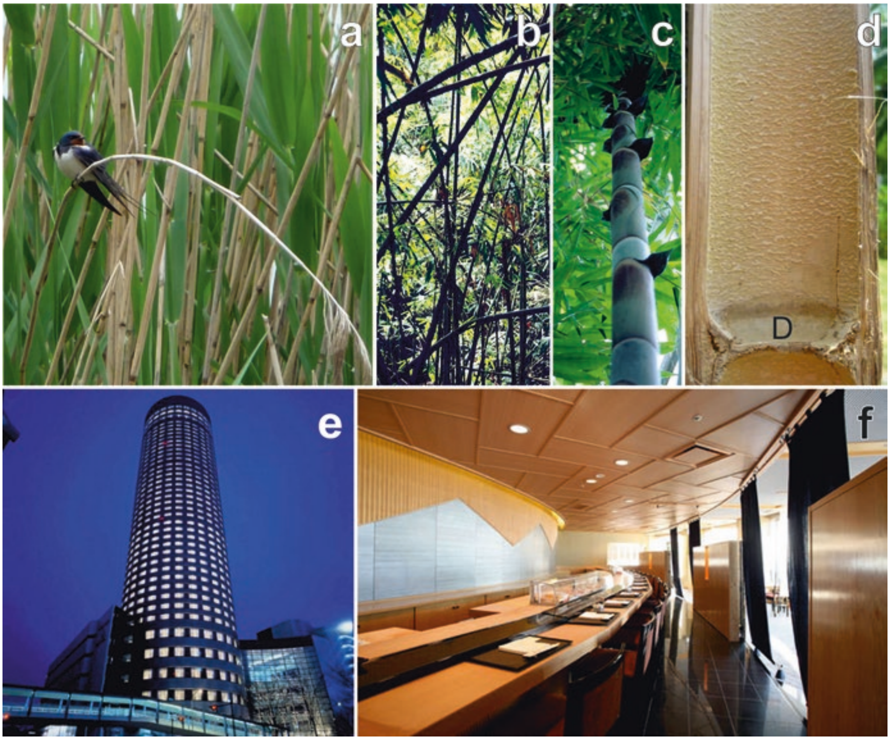

Fig. 3.19 Model grass blades. (**a**) Reed (*Phragmites australis*). (**b**–**d**) Bamboo (*Bambusa*). (**b**, **c**) Rainforest site in Thailand. (**d**) *Bambusa vulgaris*. Longitudinal section through hollow axis with diaphragm (D). (**e**) Replica of an 'earthquake-proof' hotel in Yokohama (Shin Yokohama Prince Hotel). (**f**) 'Ring restaurant' on an upper floor (on the 40th floor of 42). (Image credits **f**: https://images.meetingsbooker.com/images/venues/e14b8357b8dc49afb81241737.jpg, https://images.meetingsbooker.com/images/venues/9cfe753c189d4d868c60fb0f2.jpg; **a**–**d**: Own photographs)

3 Sophisticated Strategies of Organisms in An Ecosystem: Eating and Being Eaten, Mutualisms, Deceiving, Cheating, Killing

In the 'eating and being eaten', quasi the main theme in an ecosystem,[18] the eater is naturally at an advantage, the eaten is out of luck. Protection from being eaten is provided by shelter or camouflage. There are many examples. Consider, for instance, the species of stick insects (Bacteriidae), which mimic dry branches in body shape and colouration and are inconspicuous when perched on the branches of a woody plant, or a grass-green bush cricket *Conocephalus dorsalis* (short-winged conehead,

[18] Ecosystems are communities of life in which producers (green plants), consumers (mostly animals) and destroyers (e.g. microorganisms) are in momentary equilibrium.

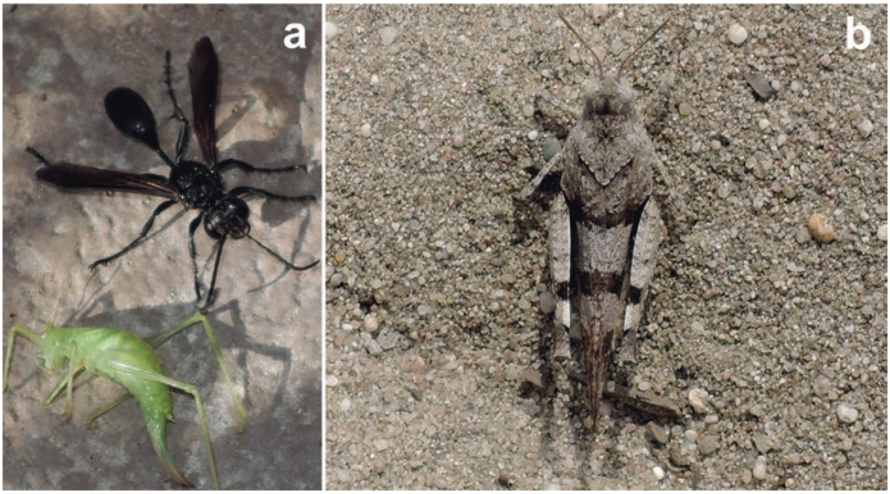

Fig. 3.20 Camouflage. (**a**) Short-winged conehead *Conocephalus dorsalis* preyed upon by the Mexican grass-carrying wasp *Isodontia mexicana* (photographed in 2020 in Heidelberg-Handschuhsheim). (**b**) Blue-winged grasshopper *Oedipoda caerulescens* (inland dunes near Sandhausen, Baden-Württemberg). (Image credit: Own photographs)

Conocephalidae; Fig. 3.20a), which is found in wet meadows. The figure also shows the prey hunter, which has nevertheless tracked down the bush cricket and transferred it to its tubular nest (e.g. in an 'insect hotel'). It is a black wasp native to Mexico called the Mexican grass-carrying wasp (*Isodontia mexicana*). This digger wasp (Sphecidae) species was introduced to southern France in the 1960s, spread from there to large parts of southern Europe and came to the middle Upper Rhine Valley in 2010.

Sandy soils, on which often lie more or less dead dark plant remains, are inhabited by *Oedipoda caerulescens* (Fig. 3.20b), which belongs to the Acrididae grasshoppers. The latter is only noticed when it flies up; its underwings are light blue, which gives it the name, blue-winged grasshopper.

Many hoverfly species are little contrasted with the background when they sit on yellow flowers or inflorescences (Fig. 3.21a, dangling marsh-lover *Helophilus pendulus* on Canadian goldenrod *Solidago canadensis*, Asteraceae). In addition, there is their visual appearance: the black-yellow banding is reminiscent of that of many wasps. Wasps have the unpleasant property of stinging for many potential predators. If, for example, birds, toads, lizards or small mammals have had a bad experience due to a wasp sting, they will refrain from such insects in the future. Unarmed insects that wear a 'wasp harness' ('Wespenharnisch') as Lunau (2011) describes it in his recommendable book, benefit considerably, because the presence of black-yellow bands or stripes is directly linked to being stung in experienced predatory animals.

Harmless insects with wasp harness are often found close together with true wasps. Figure 3.21b shows a scoliid wasp, the 'bristly dagger wasp' *Scolia hirta* on the richly flowering inflorescence of the hemp-agrimony *Eupatorium cannabinum* (Asteraceae). In the lower image section, two individuals of the large tiger hoverfly *Helophilus trivittatus* are pollinating the flowers. Along with honeybees, the marmalade hoverfly *Episyrphus balteatus* is often found on the normally wind-pollinated *Artemisia vulgaris* (common mugwort, Asteraceae; Fig. 3.21c). Perhaps the house fly *Polietes lardaria* with its black-grey banding also finds some protection. It is often found on umbellifers (Apiaceae), for example, on *Angelica sylvestris* (wild angelica), together with wasps (Fig. 3.21d).

In the course of evolution, some beetles have also been equipped with a 'wasp harness', albeit less precisely patterned. In Fig. 3.21e, a longhorn beetle from the difficult-to-identify species of the genus flower longhorn, *Strangalia*, is again found on the double umbel of *Angelica sylvestris* in the company of wasps (Fig. 3.21e). A peaceful coexistence between large earth bumblebee (*Bombus terrestris*) and a beetle with banded elytra (the hardened forewings modified as wing-cases for the hindwings), namely the Eurasian bee beetle *Trichius fasciatus* on the flower head of the common thistle *Cirsium vulgare* (Asteraceae) is not a rare to observe (Fig. 3.21f).

The banding on the elytra of flower-visiting longhorn beetles can be variable within a species. It is also variable in the bee beetle. As far as genetics is concerned, it is a 'play', and environmental influences may perhaps also play a role. We must always remember that beetles cannot choose their pattern. They rely on chance, and their patterns sometimes resemble a wasp pattern more and sometimes less. It is not so easy to find a threshold value at which effectiveness on predators ceases to exist as the pattern becomes more and more 'simplified'. The authors of the present article have often made the observation that the respective coarsely patterned insects like to stay near wasps when visiting large blossoms (inflorescences).

Experiments have shown that eyes that are often imitated on butterfly wings, e.g. in the peacock butterfly *Aglais io* (Fig. 3.22a), have a deterrent effect on predators, e.g. birds (see, for example, Vallin et al., 2005). This is also likely to be the case for other butterflies with eyespots, such as the large ringlet *Erebia euryale* (Fig. 3.22b). The same is probably true for the conspicuously large caterpillar of the elephant hawk moth *Deilephila elpenor* (Fig. 3.22c, d). The caterpillar has a relatively small head (arrows in Fig. 3.22c, d) with extremely sharp mandibles, with which it rapidly saws and eats the leaves (here of the Himalayan balsam *Impatiens glandulifera*) piece by piece. Above the area of the thoracic legs and shortly behind them, we find on both sides two 'quite scary' looking eye pair imitations. These are presented in a particularly 'perilous' manner when one gets close to the caterpillar, as the area above the pale thoracic legs inflates, and the front body moves back and forth. According to Lunau (2011), this reinforces the impression of a snake's head.

A camouflage and the associated ability to kill from ambush is well known to us from our human existence. Whether as a hunter or a terrorist or in general in 'modern' war-like conflicts or simply in a bank robbery or in trapping to kill insects or … or … man makes use of some tricks from the 'bag of tricks' of evolution, which are already many, many millions of years old.

Killing from ambush with the help of an unsurpassable perfection of camouflage can be observed (each time with great amazement!) in the flower crab spider

Fig. 3.21 Harmless insects camouflage themselves with a 'wasp harness'. (**a**) A hoverfly, the dangling marsh-lover *Helophilus pendulus* on Canadian goldenrod *Solidago canadensis*, Asteraceae. (**b**) Top left: A scoliid wasp *Scolia hirta* ('bristly dagger wasp'), right and below: large tiger hoverfly *Helophilus trivittatus* on the same inflorescence of hemp-agrimony *Eupatorium cannabinum* (Asteraceae). (**c**) Marmalade hoverfly *Episyrphus balteatus* feeding on pollen of common mugwort *Artemisia vulgaris* (Asteraceae). (**d**) A house fly (*Polietes lardaria*) with its black-grey banding likes to stay near wasps on umbellifers (Apiaceae)—here on an inflorescence of the wild angelica (*Angelica sylvestris*). (**e**) A very coarsely black and yellow banded longhorn beetle of the genus *Strangalia* close to a wasp, also on the inflorescence of the wild angelica. (**f**) A Eurasian bee beetle *Trichius fasciatus* on the flower head of the common thistle *Cirsium vulgare* (Asteraceae) together with two large earth bumblebees (*Bombus terrestris*). (Image credit: Own photographs)

Fig. 3.22 Eye imitations have a deterrent effect on predators. (**a**) Two dummy eyes on the upper wing surface of the peacock butterfly *Aglais io*. (**b**) Large ringlet *Erebia euryale*. (**c**, **d**) Caterpillar of the elephant hawk moth *Deilephila elpenor* with two eye pair mimics on both sides. The arrows point to the small head. (Image credit: Own photographs)

Misumena vatia (Fig. 3.23a). This crab spider is able to change colour: Waiting for prey (mostly flies) on white flowers or inflorescences, it takes on a white colour, on yellow ones a yellow colour. A liquid yellow dye, which is transferred from the inside of the body to the upper cell layer, is responsible for the yellow colouration. This process can take days, as can be seen from the profound description by Bellmann (2010). The colour change is triggered by the visual sense.

A further colouration occurs in the pink crab spider *Thomisus onustus*. This spider can adapt to yellow, white and light purple flowers with the appropriate colouring. It differs from the previous spider species in the shape of the abdomen. *Thomisus onustus* has an angular abdomen with the widest edge at its end; in *Misumena* the abdomen is more oval-spherical. In Fig. 3.23b a *Thomisus onustus spider* has caught a fly on the flower head of *Glebionis coronaria* (crown daisy, Asteraceae), in Fig. 3.23c a female of the pantaloon bee (*Dasypoda hirtipes*). The capture is always done in the same way: Upon the arrival of the prospective prey, the spider shoots forward with lightning speed and applies a narcotic venom to the victim between the head and thorax. A male pantaloon bee has been snatched (Fig. 3.23d)—again on *Glebionis*—by another crab spider species, namely the Napoleon spider *Synema globosum.* This crap spider has a (variable) black and yellow pattern on the longitudinal oval abdomen. Possibly ‘in the heat of the moment’ the male pantaloon bee

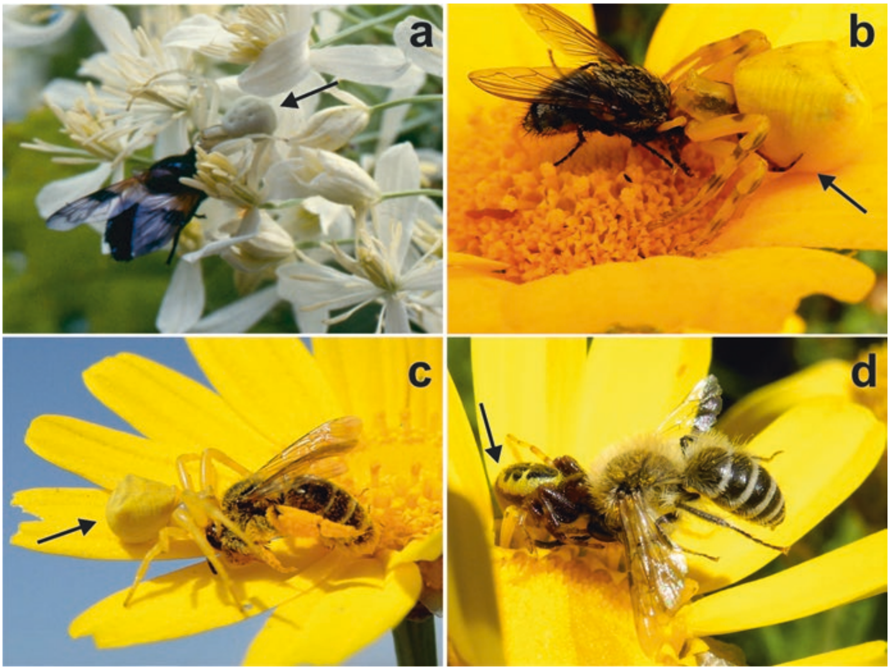

Fig. 3.23 Perfectly camouflaged predatory crab spiders (arrows) on white and yellow flowers are able to adapt their body colour to the substrate and paralyse visiting insects at lightning speed, quasi from ambush. (**a**) Flower crab spider *Misumena vatia* on the flowers of the ground virgin's bower *Clematis recta* (Ranunculaceae) with captured fly. (**b**–**d**) Catching prey on the flower heads of the crown daisy *Glebionis coronaria* (Asteraceae). (**b**) A fly was captured here by a pink crab spider *Thomisus onustus*. (**c**) pink crab spider with a female pantaloon bee (*Dasypoda hirtipes*) as prey. (**d**) Napoleon crab spider *Synema globosum* snatched up a male pantaloon bee. (Image credit: Own photographs)

mistook the predator for a female. The rich glossy yellow on the sides of the spider's abdomen perhaps mimics, albeit crudely, the richly filled 'pollen baskets' (corbiculae) on the hind legs of a female trouser bee, contrasting with the black and yellow striped abdomen. More detailed studies with regard to the bees' UV vision might provide further clues. There is sometimes a danger of over-interpretation, especially when there is great enthusiasm in observing natural phenomena.

Plants are not excluded from deceiving, cheating and killing. When angiosperms (= flowering plants) emerged about 140 million years ago, or perhaps even earlier, a magnificent interaction arose between flowers and animals (initially insects). They entered into a mutualistic relationship, a relationship based on mutual give and take: Food (pollen grains or/and nectar) for pollen transport for pollination. It is not uncommon for flowers in different relationships to have broken out of the mutualistic relationship (see e.g. Dafni, 1984; Vogel, 1975, 1993; Leins & Erbar, 2008, 2010; Erbar et al., 2017; Erbar, 2017).

Relatively 'harmless' are the free riders among the flowers. The globe orchid *Traunsteinera globosa* (Orchidaceae, Fig. 3.24 bottom right) does not produce nectar. Its inflorescences have adapted (by chance, of course!) in such a way that they resemble the inflorescences of the wood scabious or forest widow flower *Knautia* dipsacifolia (Caprifoliaceae-Dipsacoideae) in colour and shape down to the last detail. The globe orchis merely has to steal into a dense population of the knautias to get abundant insect visitation; the insects, of course, go empty-handed. The high pollinator spectrum in the *Knautia* inflorescences naturally also ensures a sufficiently high pollinator rate in the globe orchis.

Changes in the colour and shape of packaging often mislead consumers; this is where advertising psychologists are needed. People are used to organic food being packaged in green or at least partially green. Just take a look at the display cases in the supermarket these days and you will see that a green colour is often added to or even dominates the packaging of non-organic foods. In a supermarket in Madeira, mineral waters of different quality are offered with correspondingly different prices (Fig. 3.25). The most expensive mineral water on the corresponding shelf is that from the Perrier spring, known to many consumers as a noble mineral water. Why not buy the significantly cheaper 'Vidago' underneath? Intelligently placed commercially, one is unconsciously inclined to take the cheaper one, seduced by the outfit of the bottle and the label, which associatively compares itself with the 'noble water'. A discerning consumer will take time to check which water is really the better one.

Exaggeration, false promises, misleading, lies, deception characterize industrial advertising. Every day the consumer is inundated with them in the media. Intelligent (informed) consumers are less likely to be seduced. Advertising rather takes money out of the pockets of the stupid (uninformed). So are those who advertise the more clever? Flowers are neither clever nor stupid. However, they are capable of being extraordinarily successful for themselves over very long periods of time despite the mentioned false reports (e.g. Leins & Erbar, 2008, 2010; Erbar, 2017). Flowers can attract flies, for example, by putting highly exaggerated nectar dummies 'in the shop window'—appealing to the animals' feeding instinct. The grass of Parnassus (*Parnassia palustris*, Parnassiaceae) provides an impressive example (Fig. 3.26): The solitary flowers have five princess-crown-shaped organs alternating with five stamens. At the end of each coronet spike is a yellow glistening knob. In fact, they are absolutely dry knobs, but the dummies owe their drop lustre to the silk-satin-like epidermal surface (Fig. 3.27c). However, the coronet-like organs are not completely devoid of nectar; at their stalk-shaped base a little of this sweet juice is secreted from so-called nectary slits (Fig. 3.27a, b); obviously the nectar is perceived olfactorily by the flies soon after landing (Fig. 3.26b). The circular arrangement of the stalked knobs 'forces' the fly to rotate once as if on a turntable (Fig. 3.28); in doing so, it picks up abundant amounts of pollen from one anther with its ventral side of the thorax and/or abdomen; the pollen is deposited to one spot. Still closed anthers are raised one after the other above the level of the still unripe stigmas of the ovary by filament (stamen) growth (Fig. 3.26b); in favourable weather, the presentation of the five anthers lasts a total of 5 days (see Fig. 32 in Erbar & Leins, 2020). The

Fig. 3.24 The inflorescences of the globe orchis *Traunsteinera globosa* (Orchidaceae) can be mentioned as free riders among flowers. It offers the visiting insects neither nectar nor pollen in return for pollen transport for the purpose of pollination. It literally creeps into dense populations of the wood scabious or forest widow flower *Knautia* dipsacifolia (Caprifoliaceae-Dipsacoideae), to whose inflorescences it has been adapted in colour and shape down to the last detail. *Knautia* inflorescences, as generalists, show a high pollinator spectrum; left side from top to bottom: Dance flies of the genus *Empis*; large scabious mining bee *Andrena hattorfiana*; tachinid fly *Tachina fera*; violet tanbark beetle *Callidium violaceum*; right side from top to bottom: comma butterfly *Polygonia c-album*; large skipper *Ochlodes venatus*. (Image credit: Own photographs)

empty anthers are usually cast off after their filaments bend outwards. Finally, the flower is in the female phase of anthesis (Fig. 3.26c) and presents its mature stigmas in the exact same position which before was held by each anther; pollination by an insect loaded with pollen probably cannot function more precisely.

In addition to such deceptive flowers adapted to the feeding instinct of insects (in the sense of more appearance than substance), deceptive flowers have adapted unilaterally to certain behaviour patterns of insects, namely to their sexual instinct and brood-care instinct; such flowers are found again and again in most diverse relationships of flowering plants. Well-known as sex deceptive flowers are species of the orchid genus *Ophrys* (bee or insect orchids; Paulus & Gack, 1980, 1981; Paulus, 2007). Brood-site-deceit flowers are found, for example, in the Aristolochiaceae. Highly elaborate among them are the pitcher traps and slides of *Aristolochia* species (e.g. Sprengel, 1793; Vogel, 1965, 1978; Leins & Erbar, 2008, 2010; Erbar et al., 2017; Erbar, 2017). *Asarum species* also belonging to the birthwort or Dutchman's

Fig. 3.25 (Intelligent?) sales strategy on supermarket shelves. Explanations in the text. (Image credit: Own photograph)

pipe family mimic breeding sites. In the case of *Asarum caudatum*, the longtail wild-ginger from North America, breeding site deception even has fatal consequences for the brood.

It was the most important floral biologist of the twentieth century, Stefan Vogel—who continued his research into the twenty-first century and made ground-breaking discoveries—who was the first to reveal the deceptive relationship of this flower to fungus gnats (Vogel, 1978). At first glance, the flower construction (Fig. 3.29a, b) does not seem to be associated with the real breeding sites of fungus gnats. For oviposition, fungus gnats seek out moist, cool spaces ('damp crypts'), as they exist between the lamellae on the hat's underside of fruit bodies of basidiomycetes. Despite their three-dimensional dissimilarity to a fruit body of a mushroom, the flowers are regularly and eagerly visited by fungus gnats. With the flower's position close to the ground and the humid environment on the forest floor (necessary for the plant), 'fraudsters' and 'victims' are brought within a convenient proximity. The fungus gnats, whose visual perception does not seem to be well-distinctive (probably no exact vision of forms), are most probably olfactorily attracted by a scent typical of mushrooms, not perceptible to our nose. It is presumably emitted by the reddish-brown coloured sepals, especially by the tail-shaped parts. The white spots on the sepals certainly play a role in the optical short-distance orientation, but much more they act as a key stimulus with regard to the fungus gnats' ability to perceive

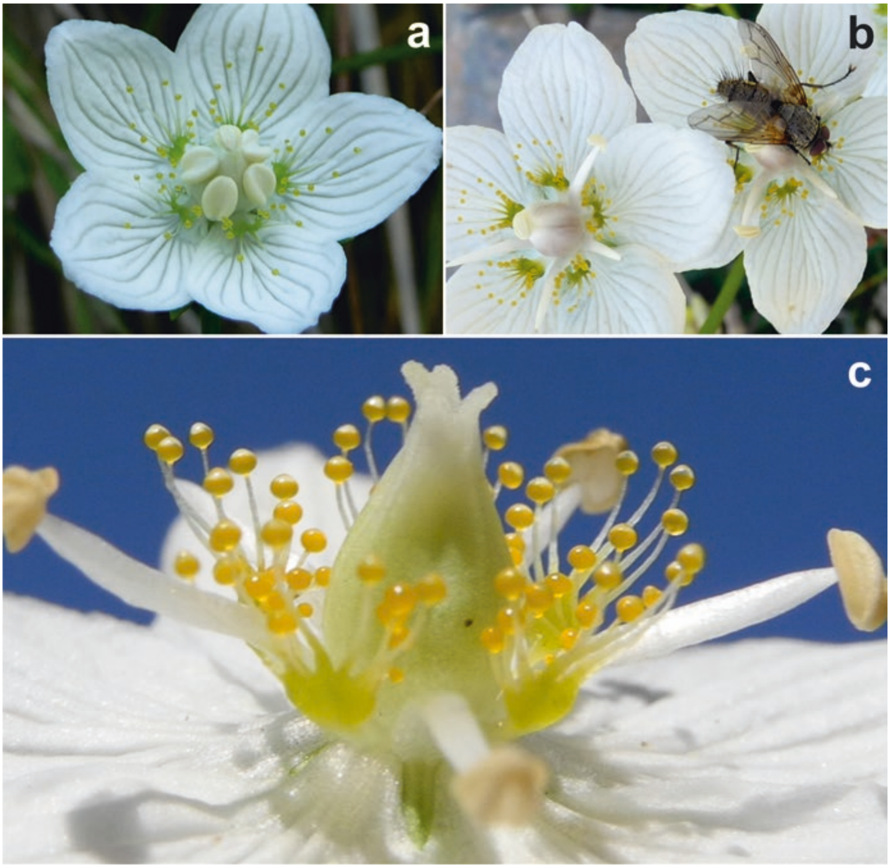

Fig. 3.26 The grass of Parnassus (*Parnassia palustris*, Parnassiaceae), whose flowers promise more than they deliver. The shiny 'nectar drops' are dry as straw, but attract plenty of flies because of their lustre. (Image credit: Own photographs)

local humidity, 'damp crypts' for example. The white patches on the sepals are covered with living hairs that secrete liquid. Indeed, female fungus gnats prefer the white patches, and during their visit, touch the stigmas or open anthers with their backs (Fig. 3.29c). Not infrequently, egg-laying occurs in this process. Eggs and the developing larvae, which can always be found in the area of the white patches, all perish after a short while (Fig. 3.29d).

4 Concluding Remarks

From the vast abundance of organismic adaptations, for this study we have selected a few examples to show the parallelism of meaningful problem solving in humans, animals and plants. They come from engineering and architecture as well as

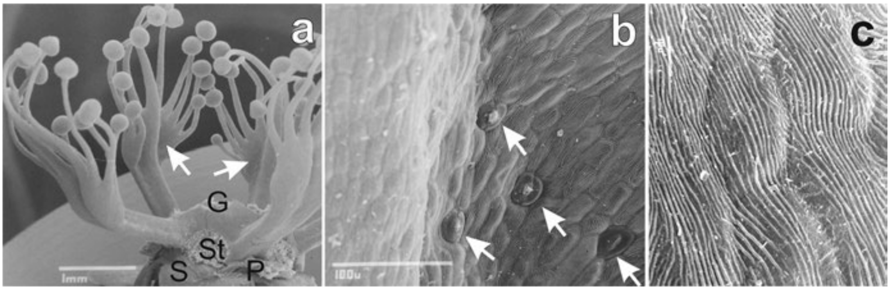

Fig. 3.27 Scanning electron micrographs of the nectar organs of the grass of Parnassus. (**a**) The boastful princess-crown-shaped floral organs bear spherical dummies of nectar drops at the end of the rays. Petals (P), stamens (St) and gynoecium (G) removed, *S* sepal. The arrows indicate the ventral sites of the digitate organs, where some nectar is being sec Petals (P), stamens (St) and gynoecium (G) removed, *S* sepal. The arrows indicate nectary slits at the basis of the digitate organs. (**b**) Nectar-secreting region of a digitate organ with nectary slits (arrows) at higher magnification. (**c**) Curved striate surface of the spherical dummy nectar drops. (From Leins & Erbar, 2010, modified)

Fig. 3.28 The flowers of the grass of Parnassus are from the perspective of flower ecology a turntable blossom. (**a–d**) Rapidly successive snapshots of a flower visitor. (Image credit: Own photographs)

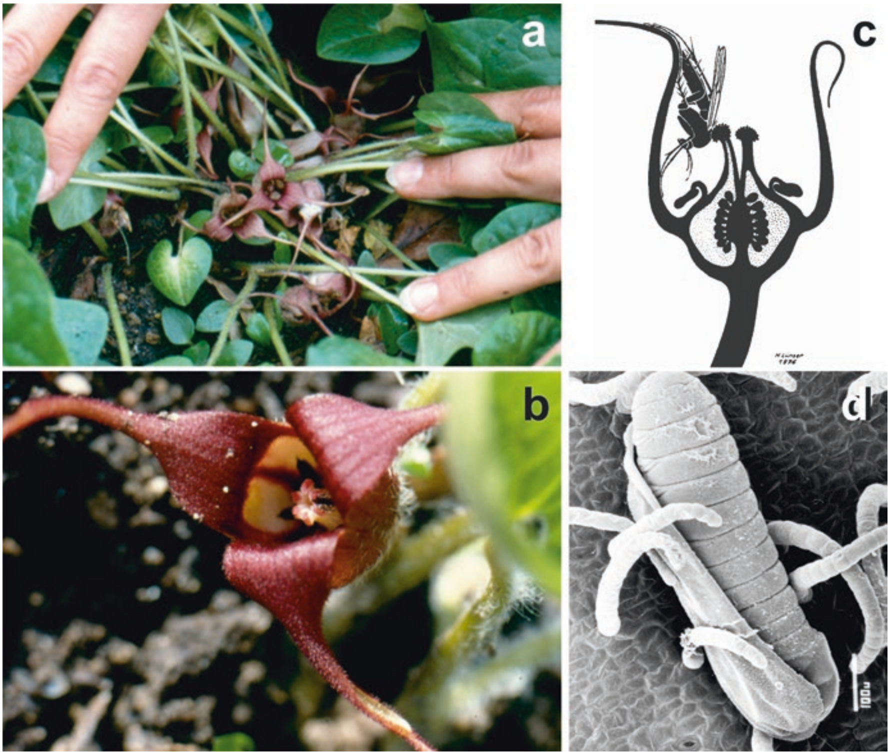

Fig. 3.29 (**a**–**d**) The flowers of the longtail wild-ginger *Asarum caudatum* (Aristolochiaceae) from North America are deceptive flowers imitating the brood-site with fatal consequences for the offspring of the visiting fungus gnats (see text). (**c**: From Vogel, 1978. Image credit **a**, **b**, **d**: Own photographs)

behaviour. We have equated optimal functioning with at the same time realisable effort (as low as possible) to an intelligent approach. This results in an intelligent product. The term ‘intelligence’ firstly suggests a nature related exclusively to human beings. In many cases, people are tempted to measure human intelligence by means of tests. These often contain a long list of intelligence factors, from which the intelligence quotient is determined. Of course, the age of the person is taken into account. An age comparison opens up interesting aspects of intelligence development or change in relation to a single individual. However, there is a danger of an essentialist approach when determining a general intelligence. This leads to a kind of standardisation. However, human beings cannot be pressed into a norm or a type. All individuals of the ‘mammal’ *Homo sapiens* are unique, just like all individuals of an animal or plant species—if one disregards cloning, which is common practice in plants. It is obvious that in such a unique specimen abilities and inabilities present themselves in most various mixing ratios. A good spatial imagination—often asked in intelligence tests—will hardly help a philosopher out of the labyrinth of contradictions within ethics. But surgeons or technicians or biologists who deal with morphology and anatomy will benefit in all their activities from an innate or learned ability to find their way in space and time.

Intelligence did not develop in humans overnight, but step by step in an evolutionary process. It probably began with the ability to learn, which can also be observed independently in other animal groups. Consider, for example, the ability to learn in ravens and crows (e.g. Taylor et al., 2012; Uomini et al., 2020). In the context of evolution, everything humans are capable of creating is a result of organismic evolution, subject to intelligent play with chance and selection. Evolution itself knows no ethics. The latter is peculiar to the human being in his 'becoming self-aware' and the consciousness that he dwells on earth as a zoon politikon (Aristotle). Chance and optimization by selection under the dictates of the economic principle (optimization principle), which triggers relentless competition, can also be called—if one wants!—as a 'creation strategy'. If one wants!, one can think about the attributes of a 'creator'. But we want to leave that to intelligent theologians and scientists dealing with comparative studies of religions, if they want it.

Acknowledgement We thank the Royal Society, London, for kind permission to use Figures 2a (here: Fig. 3.10g) and 3a (here: Fig. 3.10h) from the publication by Melzer et al. (2010), published in 'Journal of the Royal Society Interface'.

References

Barthlott, W., & Ehler, N. (1977). Raster-Elektronenmikroskopie der Epidermisoberflächen von Spermatophyten. *Tropische und subtropische Pflanzenwelt, 19*, 367–467.

Barthlott, W., & Neinhuis, C. (1997). Purity of the sacred lotus, or escape from contamination in biological surfaces. *Planta, 202*, 1–8.

Bellmann, H. (2010). *Der Kosmos Spinnenführer*. Franckh-Kosmos.

Blattner, F., & Kadereit, J. W. (1991). Patterns of seed dispersal in two species of *Papaver* L. under near-natural conditions. *Flora, 185*, 55–64.

Bowling, A. J., & Vaughn, K. C. (2008). Structural and immunocytochemical characterization of the adhesive tendril of Virginia creeper (*Parthenocissus quinquefolia* [L.] Planch.). *Protoplasma, 232*, 153–163.

Buchmann, S. L. (1983). Buzz pollination in angiosperms. In C. E. Jones & R. J. Little (Eds.), *Handbook of experimental pollination biology* (pp. 73–114). Van Nostrand Reinhold Comp.

Corbet, S. A., Chapman, H., & Saville, N. (1988). Vibratory pollen collection and flower form: Bumble-bees on *Actinidia*, *Symphytum*, *Borago* and *Polygonatum*. *Functional Ecology, 2*, 147–155.

Culjak, A. (2014). *Organisation und Devianz - Eine empirische Fallrekonstruktion der Havarie der Costa Concordia*. Springer.

Dafni, A. (1984). Mimicry and deception in pollination. *Annual Review of Ecology and Systematics, 15*, 259–278.

Darwin, C. (1859). *On the origin of species by means of natural selection, or the preservation of favoured races in the struggle for life*. J. Murray.

De Luca, P. A., & Vallejo-Marín, M. (2013). What's the 'buzz' about? The ecology and evolutionary significance of buzz-pollination. *Current Opinion in Plant Biology, 16*, 429–435.

Erbar, C. (2017). Falsche Versprechen: Lug und Trug in der Blütenwelt. *Ruperto Carola, 11*, 120–127.

Erbar, C., & Leins, P. (2018). Wie mobil sind Pflanzen? *Heidelberger Jahrbücher Online, 3*, 21–50. https://doi.org/10.17885/heiup.hdjbo.2018.0.23818

Erbar, C., & Leins, P. (2020). Entwicklungen in der Entwicklung – Fortwährende Veränderungen im Fluss der Organismenwelt. *Heidelberger Jahrbücher Online, 5*, 1–45. https://doi.org/10.17885/heiup.hdjbo.2020.0.24182

Erbar, C., Heiler, A., & Leins, P. (2017). Nectaries in fly-deceptive pitcher-trap blossoms of *Aristolochia*. *Flora, 232*, 128–141.

Francé, R. H. (1920). *Die Pflanze als Erfinder*. Franckh'sche Verlagshandlung.

Henkel, K. (1997). Die Renaissance des Raoul Heinrich Francé. *Mikrokosmos, 86*, 3–16.

Kadereit, J. W., & Leins, P. (1988). A wind tunnel experiment on seed dispersal in *Papaver* L. sects. Argemonidium Spach and Rhoeadium Spach (Papaveraceae). *Flora, 181*, 189–203.

King, M. J., & Buchmann, S. L. (2003). Floral sonication by bees: Mesosomal vibration by *Bombus* and *Xylocopa*, but not *Apis* (Hymenoptera: Apidae), ejects pollen from poricidal anthers. *Journal of the Kansas Entomological Society, 76*, 295–305.

Leins, P., & Erbar, C. (2008). *Blüte und Frucht. Morphologie, Entwicklungsgeschichte, Phylogenie, Funktion und Ökologie* (2nd ed.). Schweizerbart'sche Verlagsbuchhandlung.

Leins, P., & Erbar, C. (2010). *Flower and fruit. Morphology, ontogeny, phylogeny, function and ecology*. Schweizerbart Science Publishers.

Leins, P., & Erbar, C. (2017). *Bäume und Sträucher in Herbst und Winter erkennen. Bebilderte Steckbriefe, Wissenswertes zu Namen, Mythologie und Verwendung* (2nd ed.). Schweizerbart'sche Verlagsbuchhandlung.

Leins, P., & Erbar, C. (2018). *Bäume und Sträucher in Frühjahr und Sommer erkennen. Bebilderte Steckbriefe und allerlei Begleitgeschichten aus Biologie, Mythologie und Verwendbarkeit*. Schweizerbart'sche Verlagsbuchhandlung.

von Lengerken, A. (1885a). *Die Bildung der Haftballen an den Ranken einiger Arten der Gattung Ampelopsis*. Dissertation.

von Lengerken, A. (1885b). Die Bildung der Haftballen an den Ranken einiger Arten der Gattung *Ampelopsis*. *Botanische Zeitung, 43*, 337–346. 353–361, 369–379, 385–393, 401–410, Taf. IV.

Lunau, K. (2011). *Warnen, Tarnen, Täuschen*. WBG.

Mabberley, D. J. (2008). *Mabberley's plant-book* (3rd ed.). Cambridge University Press.

Melzer, B., Steinbrecher, T., Seidel, R., Kraft, O., Schwaiger, R., & Speck, T. (2010). The attachment strategy of English ivy: A complex mechanism acting on several hierarchical levels. *Journal of the Royal Society Interface, 7*, 1383–1389.

Michener, C. D. (1962). An interesting method of pollen collecting by bees from flowers with tubular anthers. *Revista de Biología Tropical, 10*, 167–175.

Nachtigall, W. (1997). *Vorbild Natur: Bionik-Design für funktionelles Gestalten*. Springer.

Nachtigall, W. (2007). *Natur macht erfinderisch. Das Ravensburger Buch der Bionik*. Ravensburger.

Nachtigall, W. (2008). *Bionik. Lernen von der Natur*. Beck.

Nachtigall, W., & Blüchel, K. G. (2000). *Das große Buch der Bionik. Neue Technologien nach dem Vorbild der Natur*. Deutsche Verlags-Anstalt.

Paulus, H. F. (2007). Wie Insekten-Männchen von Orchideenblüten getäuscht werden - Bestäubungstricks und Evolution in der mediteranen Ragwurzgattung *Ophrys*. *Denisia, 20*, 255–294.

Paulus, H. F., & Gack, C. (1980). Beobachtungen und Untersuchungen zur Bestäubungsbiologie südspanischer *Ophrys*-Arten. *Jahresberichte des Naturwissenschaftlichen Vereins Wuppertal, 33*, 55–68.

Paulus, H. F., & Gack, C. (1981). Neue Beobachtungen zur Bestäubung von *Ophrys* (Orchidaceae) in Südspanien, unter besonderer Berücksichtigung des Formenkreises *Ophrys fusca* agg. *Plant Systematics and Evolution, 137*, 241–258.

Pfadenhauer, J. S., & Klötzli, F. A. (2014). *Vegetation der Erde: Grundlagen, Ökologie, Verbreitung*. Springer Spektrum.

Spalding, E. S. (1905). Mechanical adjustment of the Sahuaro (*Cereus giganteus*) to varying quantities of stored water. *Bulletin of the Torrey Botanical Club, 32*, 57–68.

Speck, T. (2011). *Intelligente Kleber nach dem Vorbild der Natur*. Retrieved from https://www.biooekonomie-bw.de/de/fachbeitrag/aktuell/intelligente-kleber-nach-dem-vorbild-der-natur/

Sprengel, C. K. (1793). *Das entdeckte Geheimnis der Natur im Bau und in der Befruchtung der Blumen*. Vieweg.

Steinbrecher, T., Beuchle, G., Melzer, B., Speck, T., Kraft, O., & Schwaiger, R. (2011). Structural development and morphology of the attachment system of *Parthenocissus tricuspidata*. *International Journal of Plant Sciences, 172*, 1120–1129.

Taylor, A. H., Miller, R., & Gray, R. D. (2012). New Caledonian crows reason about hidden causal agents. *Proceedings of the National Academy of Sciences, 109*, 16389–16391.

Uomini, N., Fairlie, J., Gray, R. D., & Griesser, M. (2020). Extended parenting and the evolution of cognition. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences, 375*, 20190495. https://doi.org/10.1098/rstb.2019.0495

Vallejo-Marín, M. (2019). Buzz pollination: Studying bee vibrations on flowers. *The New Phytologist, 224*, 1068–1074.

Vallin, A., Jakobsson, S., Lind, J., & Wiklund, C. (2005). Prey survival by predator intimidation: An experimental study of peacock butterfly defence against blue tits. *Proceedings of the Royal Society B, 272*, 1203–1207.

Vogel, S. (1965). Kesselfallen-Blumen. *Umschau, 65*, 12–17.

Vogel, S. (1975). Mutualismus und Parasitismus in der Nutzung von Pollenträgern. *Verhandlungen der Deutschen Zoologischen Gesellschaft, 68*, 102–110.

Vogel, S. (1978). Pilzmückenblumen als Pilzmimeten. *Flora, 167*, 329–398.

Vogel, S. (1993). Betrug bei Pflanzen: Die Täuschblumen. *Abhandlungen der Mathematisch-Naturwissenschaftlichen Klasse. Akademie der Wissenschaften und der Literatur in Mainz, 1993*(1), 1–48.

Walter, H. (1973). *Die Vegetation der Erde in öko-physiologischer Betrachtung. Bd. I: Die tropischen und subtropischen Zonen* (3rd ed.). G. Fischer Verlag.

Walter, H., & Breckle, S. W. (1984). Ökologie der Erde. In *Spezielle Ökologie der Tropischen und Subtropischen Zonen* (Vol. 2). UTB Große Reihe.

Claudia Erbar received her doctorate (Dr. rer. nat.) from the University of Bonn after studying biology and chemistry and graduating with the first state examination in both subjects. For her state examination thesis she received the prize of the Konrad-Adenauer-Foundation for students of botany. Since 1983 she has been a research associate at the University of Heidelberg. After her habilitation in botany in 1993, she has held an extracurricular professorship since 2000 and has been research group leader for the field of 'floral biology and evolution' at the Centre for Organismal Studies (COS) Heidelberg until March 2022. Her research focuses on floral ontogeny with regard to morphological-functional questions, floral ecology (floral functions during pollination and fertilization and the interaction with insects) and the relationship and evolution of flowering plants. In teaching, she also represents plant geography.

Peter Leins studied biology, chemistry and philosophy at the universities of Tübingen, Freiburg and Munich. In Munich he received a doctorate (Dr. rer. nat.). Afterwards he was assistant, later senior assistant, at the Institute of Systematic Botany with Prof. Dr. Hermann Merxmüller. In between he learned the methodology of pollen science with Prof. Dr. Gunnar Erdtman in Stockholm. He habilitated in botany with a pollen systematic research work on a composite group. Afterwards he received a call to a professorship at the Botanical Institute of the University of Bonn. Three further appointments followed: FU Berlin, Heidelberg University, Kiel University (FU Berlin and Kiel University not accepted). At the University of Heidelberg he was first director of the Institute of Systematic Botany and Plant Geography and the Botanical Garden (later Department of Biodiversity and Plant Systematics of the newly founded Heidelberg Institute of Plant Sciences). Since 2002 he has been in research and teaching 'retirement'. His main research interests are in the fields of floral morphology and development, floral ecology, floral plant systematics, pollen science, dispersal biology, evolutionary biology and biophilosophy.

Chapter 4
Intelligence in the Animal Kingdom

Michael Wink

Abstract Among corvids, parrots, dolphins, New World and Old World monkeys, and especially the great apes, there are many species that excel in intelligence. Apparently, they can recognize a context, make plans, and find innovative solutions. Intelligent behavior can be observed in many instances: Many animals make and use tools to open nuts, shells, snails, or birds' eggs. Sticks and wires are employed to probe and spear hidden prey. Great apes use twigs to fish ants or termites out of their mounds or to get honey. Many species have invented surprising tricks to cleverly exploit untapped food sources. These tricks are passed down in populations through cultural transmission. Many animals exhibit amazing cognitive capabilities (problem-solving processes, memory, and orientation) and social intelligence. The assumption that only we humans are intelligent beings, using tools, and planning our actions, is thus clearly outdated. Apparently, the genes for intelligence were developed much earlier during evolution and are widespread in the animal kingdom. Because we humans have the largest number of neurons in our brains, we have a particularly impressive cognitive capacity among all animals. As a unique feature, we also have the ability to speak and can thus transmit innovations and thoughts particularly quickly.

1 Introduction

The term intelligence summarizes different cognitive and mental capacities to solve logical, practical, or linguistic problems. In this form, the term only fits us humans. We humans usually ignorantly and arrogantly assume that only *Homo sapiens* are intelligent beings, while animals survive only by instincts as behavioral robots

M. Wink (✉)
Institute of Pharmacy and Molecular Biotechnology, University of Heidelberg, Heidelberg, Germany
e-mail: wink@uni-heidelberg.de; https://www.uni-heidelberg.de/institute/fak14/ipmb/phazb/akwink.html; https://www.winks-biology.com

R. M. Holm-Hadulla et al. (eds.), *Intelligence - Theories and Applications*,
https://doi.org/10.1007/978-3-031-04198-3_4

genetically primed for specific behaviors, reacting only to external stimuli and learning by trial and error.

Since Plato, theologians, philosophers, and philologists have tried to separate humans from animals by unequivocal criteria. The first criterion, that man is the only bipedal animal without feathers, did not really stand the test of time, because already monkeys and especially the ancestral species leading to *Homo sapiens* were bipedal. Later, new criteria were added, all of which are connected with intelligence to some degree:

- Manufacture and use of tools,
- Warfare,
- Purposeless play,
- Cooking,
- Religiosity.

As I will explain in this article, the production and use of tools is no longer a unique selling point for humans because there are many animals that can do this as well (Becker, 2021; Hauser, 2001). From Jane Goodall's field studies in East Africa, it became known that chimpanzees can make war. Additionally, Lynda Sharpe was able to demonstrate that Meerkats play intensively in the wild. Otters have been reported to regularly play with small stones, much like children play with wooden cubes. Any owner of a dog or cat can certainly confirm the obvious and inherent playfulness of their pets. Cooking is probably indeed a unique feature of the genus *Homo*, because *Homo erectus* learned to master fire, and thus presumably cooking, approximately 1.8 million years ago. This innovation made it possible to utilize food that was difficult to digest or microbially contaminated (Frank et al., 2018). Improved nutrition was probably a prerequisite for the development of a larger brain (typical for humans and Neanderthals), which requires a lot of energy (Storch et al., 2013). Religiosity could be a unique feature of modern humans, *Homo sapiens*. Evidence for this comes from graves with burial objects that first appear with *H. sapiens* but not yet with Neanderthals.

The intelligence discussion often overlooks the fact that animals must possess considerable practical intelligence and high cognitive abilities (memory, orientation) in order to find food on a daily basis, to avoid being eaten by predators, and to reproduce successfully. If animals would not have these abilities, they would have gone extinct long ago. There is also evidence of non-instinctive intelligence, as animals often show the ability to solve complicated problems and understand causal relationships. Animals can develop new creative solutions (e.g., tools) and disseminate them via their social networks. Of course, we do not know what is going on in the brain of an animal, but we may assume that animals can think, feel, and sense. Emotionality, cognition, consciousness, learning ability, and sociability are apparently characteristics of animals, with which we are phylogenetically closely related. Different forms of intelligence can be distinguished, such as manual, economic, ecological, and social intelligence. Such forms of intelligence depend on the problems that animals have to master in their environment.

The question of whether intelligence exists in animals and how it can be studied is the object of behavioral biologists. Behavioral biology has changed its name several times over the past 160 years. As early as 1858, David Weinland coined the name *Animal Psychology*, which then became *Tierpsychologie* in Germany. This discipline dealt with the systematic and comparative study of animal behavior. Charles Darwin had also already recognized this topic and published “The Expression of the Emotions in Man and Animals” in 1872. Darwin brought evolutionary aspects into the discussion of behavior. These suggestions fell on fertile ground and were taken up and successfully developed further in the twentieth century by the behavioral scientists Oskar and Katharina Heinroth (Schulze-Hagen & Kaiser, 2019), Otto Koehler, Nikolaas Tinbergen (Schulze-Hagen, 2021), and Konrad Lorenz. Initially they called their field of research Animal Psychology, but from 1950 onward they largely used the term *Ethologie*, which was already introduced in English-speaking countries in 1920 as *Ethology* by William Wheeler. In the meantime, the term Behavioral Biology had become established. Since psychology deals with the psyche of humans, i.e., feelings, behavior, and consciousness, the term *Behavioral Biology* is more appropriate than *Animal Psychology* because we can only analyze the behavior of animals and can only indirectly draw conclusions about their psyche from this.

2 Tool Use in the Animal Kingdom

When anthropologists find traces of early humans or even older ancestors, evidence of tool use is often used to assign the finds to the genus *Homo*. This is because tool use had been generally considered to be an intelligent trait and a unique feature by which humans can be identified. However, there are many observations that mammals and birds also use tools, mostly to reach hidden food in crevices and holes or food in shells (nuts, mussels). An organism, which uses or makes tools must have understood the underlying problem and found a solution to solve it, or learned it from other conspecifics. It must therefore have understood the function and utilization of an object. The purposeful use of an object turns it into a tool. Some animals modify an object to optimize it as a tool. This is the realm of technical intelligence. However, organs of an animal are not considered tools in our context, even if we talk about chewing or gripping tools (Becker, 2021).

Intelligent behavior and tool use are often learned. Some variants of tool use could also have a genetic base (see Bearded Vulture, Song Thrush); others are clearly new inventions that are culturally transmitted. In squirrels, the general ability to gnaw nuts has been found to be genetically inherited. However, individuals learn very quickly through experience which technique is best suited. This is true for many animal (and human) behaviors. For tool use, also some intermediate stages exist, in which nature and nurture complement each other, similar to the situation with many other behavioral traits (Eibl-Eibesfeldt, 1972).

2.1 Hammer and Hammering

A hard shell protects many energy-rich plant seeds. In the course of evolution, some animals have specialized through particular adaptations to open such hard-shelled seeds or fruits to obtain the energy-rich kernels. Think, for example, of the teeth of rodents (mice, squirrels), which can gnaw even the hardest nut, or the beaks of woodpeckers, which open nuts by hammering, or the strong beaks of grosbeaks, which can easily crack smaller seeds. These adaptations are clearly genetic in nature, although the performance of nut-cracking can be improved through learning and experience.

This is in contrast to animals that use stones as tools to crack hard-shelled food, so-called *hammering*. This behavior tends to be learned and is passed on in populations. In hammering, two variants can be distinguished: (1) an animal takes a stone or similar hard object in its beak or paws and uses it to hammer hard-shelled objects, and (2) an animal throws a stone at hard-shelled food, such as an ostrich egg, to crack it (Becker, 2021).

2.1.1 Hammer

Three corvid species are known among birds that use tools to open objects. The Australian White-winged Chough (*Corcorax melanorhamphos*) feeds among other things on freshwater mussels. To open these mussels, choughs look for an empty mussel shell and use it to pound on the live mussels until they open. They can also throw the mussels on rocks to crack them. Hammering is less well documented for American Crows (*Corvus brachyrhynchos*) and Fan-talied Ravens (*Corvus ripidurus*) (Becker, 2021). The African Openbills (*Anastomus lamelligerus*) open snails and shells with their beaks alone and not with the aid of tools, as was previously assumed (Becker, 2021).

Hammering is more common among mammals, especially primates. Among predators, the American Sea Otter (*Enhydra lutris*) is known to prey on large marine snails, especially abalones (genus *Haliotus*). These snails can reach a diameter of up to 25 cm. They cling tightly to underwater rocks and cannot be easily dislodged. To reach this food, sea otters look for large stones (up to 1.5 kg in weight), which they hold in their paws. With these, they dive down to the mussels and hammer the stone on the mussel until a hole is made. Through this hole, the sea otters use their paws to extract the shell's guts and then wait for the shell to die. Later, the sea otters detach the dead abalone from the rock, bring it to the surface and consume it while swimming on their backs.

Primates are known for their intelligence. Thus, it is not surprising that they use tools to crack hard-shelled food (nuts, mussels). Such behaviors are known from the New World monkeys (capuchins), Old World monkeys, and the great apes. In nature, stones or pieces of hardwood are used as tools. In captivity, many other objects were selected for hammering. In nature, regular anvil places were observed, to which the monkeys transported the nuts. Hammering is learned, and in capuchin monkeys, males use this technique more frequently and intensively than females (Becker, 2021).

Among Old World monkeys, only two species are known to use hammers: Chacma Baboon (*Papio ursinus*) and Long-tailed Macaque (*Macaca fiscicularis*). Macaques open shells and snails by placing the food on an anvil and then cracking it with a stone. The young monkeys learn from the adults and do not master this technique until they are two and a half years old. This technique has now become quite common to the point that mussels have already become rare in areas with macaques. Chacma Baboons use stones to crack fruits of the baobab. Mainly young male baboons learned this technique (Becker, 2021).

Among the great apes (gorilla, orangutan, chimpanzee, and bonobo), hammering has developed in a particularly refined manner in chimpanzees and bonobos, while orangutans sometimes hammer open termite mounds; gorillas apparently do not know these techniques at all. Only chimpanzees in West Africa have developed the tradition of cracking nuts with stones. The chimpanzees in East and Central Africa have not yet figured out the trick. Hardwood or stones are used as tools, and tree roots as anvils. It is mainly the mothers who use this technique and pass it on to their children, especially their daughters. Stones used for cracking objects can weigh several kilograms, which are lifted with both hands and slammed down on a nut. Apparently, chimpanzees have understood the connection between anvil and hammer. In West Africa, stones with signs of utilization have been found that were probably used by chimpanzees 4300 years ago. These stones were of a size that fit well in chimpanzee hands, so *Homo sapiens* were probably unlikely to be the tool user. Hammering behavior is not genetically fixed, but must be learned. It was probably passed down from one generation of chimpanzees to the next. Bonobos behave similarly to chimpanzees, but their tool use is less well documented (Becker, 2021).

2.1.2 Cracking Eggs

Cracking eggs involves taking a stone in the beak or hand and throwing it at a hard-shelled food. Unlike hammering, this technique does not require an anvil.

The Egyptian Vulture (*Neophron percnopterus*) apparently uses stones to open large eggs, such as those of an ostrich. This was first described in the nineteenth century and intensively studied in the twentieth century. An Egyptian Vulture can carry a stone weighing up to 1 kg in its beak to an ostrich nest to crack the eggs. Smaller eggs are thrown on the ground until they crack. These behaviors appear to be derived from social behavior, but the cracking egg technique is learned and culturally transmitted (Eibl-Eibesfeldt, 1972). It is possible that the Australian Black-breasted Buzzard (*Hamirostra melanostermon*), Cape Crow (*Corvus capensis*), and the African Pied Crow (*Corvus albus*) also use stones to open eggs in a similar manner to Egyptian Vultures (Becker, 2021). Among mammals, mongooses apparently use the stone trick to crack eggs. Polar bears are said to use ice chunks to stun seals (Becker, 2021).

2.1.3 Anvil

Hammering requires a solid surface (flat stone, rock, tree trunk) to serve as an anvil. A number of animals use an anvil but not a hammer. They take the object to be opened in their beak or paws and hit it on the anvil.

Wrasses of the genus *Cheilinus* have been reported to grasp sea urchins and mussels with their mouths, then swim to a reef rock and pound the prey on it. Since not all wrasses can do this, it is assumed that a learning process must underlie this behavior.

In birds, anvil use is widespread when it comes to cracking hard-shelled food (insects, snails) or beating prey to death. Snail anvils have been reported for Ruddy Kingfisher (*Halcyon coromandra*), for a now extinct cuckoo (*Coua delandei*), for Noisy Pitta (*Pitta versicolor* and four other species), for Tooth-billed Bowerbird (*Scenopoeetes dentirostris*), for Southern Booboo (*Laniarius ferrugineus*), for Song Thrush (*Turdus philomelos*), for Blackbird (*Turdus merula*) and other thrushes, and occasionally for Stonechat (*Saxicola rubetra*), Pied Flycatcher (*Ficedula hypoleuca*), and for Blue Whistling Thrush (*Myophonus caeruleus*) (Becker, 2021). Some birds smash their prey several times against an anvil to kill it; this is known from Yellow-legged Gulls (*Larus michahellis*), Egyptian Vultures (*Neophron percnopterus*), Black-legged Seriema (*Chunga burmeisteri*), Eurasian Bee-eaters (*Merops apiaster*), Eurasian Kingfishers (*Alcedo atthis*), and other species.

Sea otters, which we have already met as tool users, can also take snails and shells in their forepaws and hammer them on an anvil until they crack open. Among primates, anvil use is not widespread and apparently learned: only a few New World capuchin monkeys bash nuts, eggs, or solid fruit against tree trunks to crack them. Among Old World monkeys, only baboons and chimpanzees open nuts or turtles using anvil techniques (Becker, 2021). In a variant of the anvil, the food item is fixed in clefts or small crevices. This is known, for example, from the Great-spotted Woodpecker, which occupies traditional "anvil places" to open the cones of pine or spruce.

2.2 Cracking Nuts and Bones

If you have no tools, how can you obtain food in solid shells (nuts, mussels, snails) or in bones?

Birdwatchers have long known that crows and rooks have invented a clever way of cracking nuts. They look for a walnut, fly up with it and then drop it from the air onto a hard surface, such as a road (Fig. 4.1). If all goes well, the nut bursts open on impact and its contents can be eaten. In the vicinity of Heidelberg, hundreds of Carrion Crows and Rooks are frequently seen under walnut trees in autumn and winter, deliberately searching for nuts and cracking them in the manner described. The trick is obviously well known.

Fig. 4.1 Rook with walnut. (Photo: M. Wink)

An improvement of this tactic was reported by Japanese Carrion Crows, which love the Japanese walnut (*Juglans ailanthifolia*). Instead of repeatedly flying up with the nuts, the crows in the Japanese city of Sendai deliberately placed the nuts in front of the wheels of slow-moving cars. This allowed the nuts to be cracked quickly and the kernel to be eaten. Gradually, crows in other Japanese cities (but not in Europe) have learned the trick. Some crows select traffic lights to place the nuts specifically in front of the wheels of cars waiting at red lights. After the cars ran over the nut when the light turned green, the crows waited for the red phase to eat the cracked nut (Schilthuizen, 2018). Besides nuts, several corvids (Rook, Carrion Crow, Hooded Crow, Jackdaw, Common Raven, New-Caledonian Crow) have learned to crack mussels and periwinkles by throwing them (Becker, 2021).

The trick of dropping hard-shelled prey from a great height onto a hard surface is also known from Great Skuas (*Stercorarius skua*), which drop penguin eggs from the air, or from Herring Gulls (*Larus argentatus*) and other gull species in America and Australia, which do this with whelks, crabs, sea urchins, and mussels (Becker, 2021). The egg-throwing method, mentioned before, is mastered by quite a few other bird species, such as Egyptian Vultures, Marsh Harriers (*Circus aeruginosus*), and Seriema. Another variant has been invented by the Sharp-beaked Ground Finch (*Geospiza difficilis*) on the Galapagos Island of Wolf; it deliberately rolls gannet eggs against rocks so that they burst open.

Among the birds of prey, the Bearded Vulture (*Gypaetus barbatus*) has developed a special technique to reach the nutritious marrow of tubular bones that usually remain after Griffon Vultures have visited a carrion. Bearded Vultures take remaining bones in their beaks or talons (Fig. 4.2) and drop them on special rocks from a height of about 500 m. There the bones burst open, the Bearded Vulture flies to such ossuaries or bone-breaking sites and tries to find the marrow. It can also swallow and digest smaller pieces of bone (Margalida et al., 2020). Golden Eagles (*Aquila*

Fig. 4.2 Bearded Vultures pick up bones from the carrion site and drop them over rocks ("ossuaries"). There the bones burst open and the Bearded Vultures can eat the energy-rich bone marrow. (Photo: M. Wink)

chrysaetos) and Bald Eagles (*Haliaeetus leucocephalus*) have been reported to prey on turtles using the Bearded Vulture technique.

A variation of the throwing technique is the use of stones or branches for defense. Some birds throw these objects from the air at attackers, e.g., humans approaching a nest. There are mostly anecdotal reports of this from Arctic Terns, Ferruginous Hawks, Verreaux's Eagle, Common Ravens, Carrion Crows, and Jackdaws (Becker, 2021). As known from zoos, monkeys and elephants also like to throw stones and branches at keepers and visitors. In nature, throwing stones and branches is part of the behavioral repertoire of capuchins, macaques, baboons, and especially orangutans and chimpanzees to defend themselves against enemies, for impressing behavior, or to acquire prey (Becker, 2021).

2.3 Fishing with a Bait

Striated Herons (*Butorides striata*) deliberately throw small pieces of branches or flies into the water as bait to attract fish. The herons wait motionless and then pounce with their pointed beak as soon as a fish appears. Similar behavior is also part of the behavioral repertoire of Green Herons (*Butorides virescens*) and Squacco Herons (*Ardeola ralloides*); however, other heron species use bait only rarely (Becker, 2021).

2.4 Poking and Angling

When food is in holes or other hidden places, intelligent animals can probe or spear it using hooks or sticks. Such tool use is known from some bird species, elephants, and several monkey species.

Cockatoos belong to the highly inventive parrots. They look for sticks to obtain hidden prey. In doing so, they can shorten sticks that are too long. Cockatoos also hide their tools for later use. This tool use is learned and passed on by tradition (Becker, 2021).

Famous for the use of thorns to probe food are the Woodpecker Finches (*Camarhynchus pallidus*) on the Galapagos Islands (Fig. 4.3). These Darwin finches look for a small stick or cactus thorn and use it to probe for food in small crevices. If they find food while probing, they open the cavity with their beak to get to the prey. There may be a genetic predisposition for this behavior. However, the actual tool use must be learned (Becker, 2021). Various nuthatch species, tits, and other songbirds also use sticks (at least occasionally) for probing.

As you might expect, corvids are particularly resourceful when it comes to poking and probing. The New-Caledonian Crow (*Corvus moneduloides*) feeds on insect larvae, which it pokes out of tree bark crevices with tools. Yet the production of these poking tools is quite complicated and apparently not innate. These tools are reused. New-Caledonian Crows are obviously intelligent, acting rationally by understanding causal relationships and drawing conclusions from cause and effect. The use of small sticks has also been reported for Inka Jays (*Cyanocorax yncas*), Blue Jays (*Cyanitta cristata*), Slender-billed Crows, Hawaiian Crows, House

Fig. 4.3 Woodpecker Finch with prey on Santa Cruz Island. (Galapagos Islands; Photo: M. Wink)

Crows, and American Crows. Common Ravens may even purposefully bend wires to better target their prey (Becker, 2021).

Poking behavior is well-documented among primates. Among the New World monkeys, this behavior is known from capuchin monkeys, among the Old World monkeys from macaques and gibbons. Mandrills, Green Monkeys, and macaques use sticks to reach parts of the body that they cannot reach with their hands or legs.

What about the great apes: Gorillas use sticks specifically to fish termite larvae out of a termite mound. More famous are the orangutans, which can also be seen in many zoos poking for insects or honey from holes or crevices with long sticks (Fig. 4.4). Orangutans collect a supply of sticks of different lengths, which they use as needed. This behavior is learned and young apes learn the behavior from observation. The use of sticks to catch termites and ants in chimpanzees and bonobos is also well documented.

Apes can spend several hours a day poking for insects. It is not until the age of three that a young chimpanzee masters the art of termite fishing. Since chimpanzees love sweets, they have also learned how to use sticks to dip honey. Chimpanzees also use sticks to clean their teeth or use stout sticks in fighting.

Wolfgang Köhler published observations on intelligent tool use in chimpanzees as early as 1921 (Köhler, 1921). In the experimental setup, the researchers hung bananas from the ceiling of the cage, which also contained several boxes and sticks. Chimpanzees quickly learned how to stack boxes to reach the food hanging high, or they combined the use of boxes with that of a stick. In doing so, they learned the sequence of actions not only by trial and error, but obviously by thinking.

Fig. 4.4 Orangutan at San Diego Zoo (USA), poking with sticks in artificial holes. (Photo: M. Wink)

3 Transmission of Tricks

Many animals are known for their ability to learn quickly, especially when it comes to food acquisition. The animal must recognize a food source and know how to exploit it. Examples would be the opening of nuts by squirrels, or prey capture by polecats and frogs (Eibl-Eibesfeldt, 1972). Many mammals and birds learn from their parents, especially the mother, what to eat and how to access food. This can create traditions that are passed down in families. Stumb-tailed Macaques in Japan were reported to start washing Sweet Potatoes in a puddle or stream before eating them. The behavior was first observed in 1952, and by 1962 over 75% of all macaques were washing their Sweet Potatoes (Eibl-Eibesfeldt, 1972).

It has been known for over 100 years that Great Tits (*Parus major*) or Blue Tits (*Cyanistes caeruleus*) had learned to open milk bottle tops to reach the cream sitting on top, first in England and later in other European countries. At that time, milk bottles were delivered to customers' doorsteps by a milkman each morning and deposited there. Apparently, a few particularly curious titmice had figured out the trick of how to open milk bottle lids. Even though the dairy industry changed lids, the titmice quickly learned how to crack them too. It became apparent that these tricks were passed on to more titmice that observed and then imitated the behavior. Presumably, however, this behavior arose not just once, but several times and independently of each other. Since customers buy their milk in the supermarket today and there are no more milkmen, this behavior has also disappeared (Schilthuizen, 2018).

Lucy Aplin and colleagues (University of Oxford; currently MPI for Behavioral Biology in Konstanz) tested how quickly Great Tits learn tricks to find hidden food and how this knowledge can spread. For this purpose, special feeders containing mealworms—a popular food for titmice—were set up in an experimental area where many hundreds of titmice were breeding. To obtain these mealworms, the titmice had to learn to push aside a sliding door attached to the side of the box. First, 10 titmice in the aviary were trained to specifically open the sliding doors. Then these trained titmice were released in different areas of the experimental site, where several of such feeders were located. Only in the subpopulations where trainer tits had been released did all the other tits quickly learn the trick, while in subpopulations without trainers hardly any tits learned the trick on their own. Apparently, birds also have social networks through which practical knowledge can be passed on (Schilthuizen, 2018).

Another example of birds that have learned to snatch food from people's tables includes Barbados Bullfinches (*Loxigilla barbadensis*). These bullfinches had apparently found out that the sugar in the sachets for sugar, which are usually on the table in a restaurant, tastes great. The bullfinches flew to the table, seized a sugar sachet, fixed it with one foot, and hacked a hole in it with their beaks. Then the sugar crumbs were quickly swallowed before a guest noticed the thieves and chased them away. Jean-Nicolas Audet and Simon Ducatez then did further experiments with

Barbados Bullfinches and found that urban bullfinches learned the sugar trick much faster than rural birds (Schilthuizen, 2018).

The prerequisite for explorative behavior, as observed in crows, titmice, and bullfinches, includes daring and explorativeness (neophilia). Such traits, presumably genetically controlled, appear to be widespread in urban birds. Birds in our urban environment have apparently undergone an evolutionary selection process so that ultimately stress-tolerant, less fearful birds with reduced flight distance evolved, characterized by daring and explorativeness that promote and enable intelligent performances.

4 Planning and Insight

Some animals cache food items when there is more food available than can be eaten. For example, European Jays hide nuts and acorns, European Nutcrackers cache pine cones, and nuthatches hide smaller seeds. Different places are selected and not everything is cached in a single hiding place. These birds have excellent memory as well as orientation and will find these food caches weeks and months later when food is scarce. However, they are not perfect. They overlook or forget some caching places; this benefits the plants, because in this way the seeds are spread. Jay and European Nutcrackers thus play an important function in forest ecosystems to maintain their diversity.

In general, animals have an unusually good memory for places and thus find their breeding and wintering territories without problems. This is particularly striking in migratory birds. Some species apparently have a solar and magnetic compass with which they can navigate. Many species also learn their migration route via landmarks and can navigate via them (this is referred to as landmark orientation; Wink, 2014).

Through training experiments, behavioral scientists realized early on that many animals are capable of remarkable behaviors that must be associated with higher brain power. These behaviors require abstraction and generalization. This is particularly evident in tool use, which we have already explored. In general, we can observe that ingenious tool use arose multiple times and independently during evolution in the animal kingdom. All of these behaviors require that an animal must have developed a concept to utilize a tool for a specific purpose. This requires insight and intelligence. Role models are often imitated and cultural traditions in tool use can emerge in populations. Tool use can no longer be considered a unique feature for *Homo sapiens*, even though we have developed it into a special skill. What sets us apart from other animals is our capacity for recollection, anticipation, reflection, and responsibility (Storch et al., 2013). Very likely, precursors to these traits should exist, at least in the great apes.

Domestic dogs usually know their owners very well and can anticipate events. If a dog owner throws the stick into the sea at an angle on a beach, one would expect the dog to follow the direction of the throw. However, it has been reported, that the dog first ran along the shore until it came closest to the stick, only then jumping into the water to retrieve the stick (Becker, 2021). To optimize this process in this way, the dog must be intelligent, be able to think, and perform causal planning. Apparently, dogs have a simple ego-consciousness and their mental abilities correspond to those of a two and half year old child.

5 Cognition and Social Intelligence

Onur Güntürkün from the University of Bochum describes an experiment with a Magpie (*Pica pica*; Güntürkün, 2020). The researchers attached a yellow paper sticker to the throat of a Magpie, whose head had previously been covered with a cloth so that the Magpie could not see what was going on. Then they released it without the head covering in a room with a mirror. The magpie immediately recognized itself in the reflection and saw the sticker, which it immediately removed. If there was no mirror or if a black sticker was used, the magpie was not bothered by the sticker. Such behaviors are considered evidence for self-recognition in great apes. Recognizing oneself in a mirror is known for orangutans, chimpanzees, Indian elephants, and dolphins, all mammals with large brains. In addition to the magpie, other corvids and parrots are among the birds that show higher cognitive abilities. Although birds have a different brain structure and much smaller brains than mammals, they still show a similar capacity when it comes to learning, self-awareness, and decision-making. Birds can recognize causal relationships, plan the future, or forge alliances with conspecifics (Heinrich, 1999; Güntürkün, 2020). We can therefore assume that the intelligence of corvids and parrotsParrots corresponds to that of apes.

Besides technical intelligence, social intelligence exists in many animals. Primates and dogs are famous for their social intelligence. Can birds do the same? Crows and rooks live together in flocks and are therefore predestined for such a task. In the case of Common Ravens, it has been found that they build up a social network, especially via calls, through which they are better able to access food, find hidden prey, or defend themselves (Güntürkün, 2020). Common Ravens can recognize when they are being observed. They recognize what other birds can see or not see; this is called "Theory of Mind."

As a rule, land animals are more intelligent than animals that live in water. Possibly the more monotonous environment of the marine environment was less demanding than land habitats. Dolphins and other whales are an exception, which can perform amazing cognitive feats. Whales have their own sophisticated songs, which they use to structure their social networks and use echolocation to capture their food.

Hand-raised ravens can apparently solve mental exercises; they seem to consider possible solutions in their brain in order to arrive at the correct solution in the first attempt. In addition, ravens can make plans for the future. But not all intelligent-seeming behaviors stem from an active thought process; many occur instinctively and are innate. The biologist can show this by so-called Kaspar–Hauser experiments, in which young animals are raised without contact wirh role models (Heinrich, 1999). It can be shown, for example, that many vocalizations in animals have a genetic basis, although learning often plays an additional role.

At the beginning of the twentieth century, "der kluge Hans—clever Hans," a horse in Berlin, attracted a lot of attention, because the horse could count, supposedly handle fractions, and had other arithmetic skills. However, the horse was only intelligent when the tasks were set by its trainer. Apparently, the horse had social intelligence and could guess from small gestures of the trainer what the correct answer must be (Gundlach, 2006).

Dogs can easily be trained and show amazing memory skills. The Border Collie Rico, for example, was able to match 260 words to the corresponding toys or objects and fetch toys from an adjoining room on command. One could now argue that the Collie had a good memory. In one experiment Rico was presented with seven known toys and one unknown toy, say a cat. On the command, "Rico, where is the cat?" he usually selected the cat. He evidently knew that things have names, and now that a new name was asked for, he correctly combined that this must be the cat. Similarly to young children, Rico showed comparable abstraction and learning skills. Brain scans have shown that dogs not only understand the meaning of words but also the emotional content of what is said. The meaning of words and emotional content are processed in different brain areas.

The female gorilla Coco learned American Sign Language and primatologist Penny Patterson taught Coco 1000 gestures. Coco could combine expressions and understood about 2000 spoken English words. Similar results were obtained with other primates; however, they never progressed beyond the language ability of infants.

The sea lion Rocky learned to memorize 90 graphic symbols. Rocky could sort symbols into meaningful groups and learned to interpret perspectives.

Parrots can achieve a similar level of cognitive performance as primates. For example, the Grey Parrot (*Psittacus erithacus*) Alex was able to categorize actions and distinguish over 100 objects by shape and color, as well as comprehend numbers up to eight. This parrot had an understanding of relative proportions and could tell when objects were missing. Alex was able to answer questions about his preferences and possessed cognitive abilities in some areas equivalent to those of a 5-year-old child (Güntürkün, 2020). Apparently, Alex had a concept, that is, an abstract idea of an object.

Even pigeons, whose brains are even smaller than those of crows, magpies and parrots, achieve amazing cognitive performances. Thus, trained pigeons could remember up to 7254 abstract patterns and recognize logical connections (Güntürkün, 2020).

Collective or group intelligence can already be observed in invertebrates, think of the social insects such as bees, ants, and termites that live in complexly structured states, are connected to each other in clear social networks and make intelligent decisions by working together. Communication, genetic relatedness, and learned behaviors enable an insect colony to function. The collective virtually forms a superorganism with specific group intelligence.

6 Brain Structures

Birds lack a cerebrum with the cerebral cortex (neocortex), which is considered the site of cognitive performance in mammals. In the neocortex, neurons are arranged in a special way so that complex networks (connectome) can be built. Instead, birds have a dorsal telencephalon (pallium) whose stratification and basic circuitry resemble those of the cerebral cortex and are therefore similarly powerful (Güntürkün, 2020).

The size of the brain is not automatically decisive for intelligence. Instead, intelligence depends on the number of neurons in the brain. The number of neurons in birds is approximately one billion, in chimpanzees 7.4 billion, and in humans approx. 86 billion; apparently, the more neurons, the higher the intelligence. Neurons are more densely packed in the bird brain than in the mammalian brain. Ultimately, cognitive abilities depend on the processing speed and storage capacity of neural networks (Güntürkün, 2020). Among animals, some are particularly intelligent. In mammals, intelligent species have more neurons, whereas in intelligent birds the neuron density is increased, so that the distance between individual neurons is reduced, which can therefore exchange information more quickly (Güntürkün, 2020).

7 Outlook

In many cognitive areas, corvids and parrots can rival apes:

- they use tools,
- they play Memory after appropriate training,
- they can imagine what others think,
- they show self-control over tasty temptations,
- they recognize causality behind events and can plan for the future,
- they can recognize correlations and draw appropriate conclusions,
- they can learn spelling rules for short words,
- they can recognize patterns (also distinguish works of art),
- they have some understanding of numbers,
- they have an excellent short-term memory,
- they can recognize themselves in the mirror.

The question arises whether these cognitive traits arose independently in birds and primates during evolution, or whether the last common ancestor of birds and mammals already possessed these traits 320 million years ago (Storch et al., 2013). Taking into account that squids (i.e., mollusks) and insects also already exhibit intelligent behavior, the origins of intelligence could be significantly older. Since all living things must constantly master problems in their environment, cognitive performance and consciousness could also have arisen multiple times and convergently.

Comparative genome analyses should be able to answer these questions once the relevant genes have been identified.

In the animal kingdom, not all species are equally gifted. Among invertebrates, octopuses (cephalopods) can produce amazing cognitive performances. They are particularly adept at learning and have an excellent spatial memory. For example, they can use their suction cups to twist open the screw-on lid of a jar in which delicious food had been placed (Becker, 2021). They cannot, however, recognize themselves in the mirror, as we had seen in the case of the Magpie. Among mammals, great apes, as well as many other primates, elephants, and dolphins, are considered highly intelligent. *Homo sapiens* are closely related to apes, especially to chimpanzees and bonobos. We had common ancestors approximately 7 million years ago (Storch et al., 2013). Therefore, it is actually not surprising that many of our cognitive abilities are present in the great ape. Nevertheless, we are certainly the smartest ape. Moreover, we are the only recent animal species to possess the ability to speak and write. This enables us to pass on and transmit our thoughts and experiences quickly and over a large distance. These unique features enable us to communicate our thoughts and ideas to others verbally or in writing. This is a faster process than copying behaviors by simple observation.

References

Becker, P.-E. (2021). *Wie Tiere hämmern, bohren, streichen. Werkzeuggebrauch und Bandbreite der Kultur bei Tier und Mensch* [How animals hammer, drill, paint. Tool use and range of culture in animals and humans]. Hirzel.

Darwin, C. (1872). *The Expression of the Emotions in Man and Animals*. John Murray.

Eibl-Eibesfeldt, I. (1972). *Grundriß der vergleichenden Verhaltensforschung. Ethologie*. [Ethology: Biology of behavior] (Vol. 3). R. Piper & Co.

Frank, G., Linster, L., & Wink, M. (2018). *Karotten lieben Butter. Eine Sterneköchin, ein Arzt und ein Wissenschaftler über traditionelles Kochwissen und gesunden Genuss* [Carrots love butter. A star chef, a doctor and a scientist on traditional cooking knowledge and healthy consumption]. Knaus.

Gundlach, H. (2006). Carl Stumpf, Oskar Pfungst, der Kluge Hans und eine geglückte Vernebelungsaktion [Carl Stumpf, Oskar Pfungst, Kluge Hans, and a successful deception operation]. *Psychologische Rundschau, 57*, 96–105.

Güntürkün, O. (2020). Verhaltensforschung. Federvieh mit Köpfchen [Behavioral science. Birds of a feather with brains]. *Spektrum der Wissenschaft, 30*, 1–21.

Hauser, M. D. (2001). *Wilde Intelligenz. Was Tiere wirklich denken* [Natural intelligence. What animals really think]. C.H. Beck.

Heinrich, B. (1999). *Mind of the Raven. Investigations and adventures with wolf-birds*. Harper-Collins.

Köhler, W. (1921). *Intelligenzprüfungen an Menschenaffen* [Intelligence tests on great apes]. Springer.

Margalida, A., Wetterauer, B., Domhan, C., Schulze-Hagen, H., & Wink, M. (2020). What do minerals in the feces of Bearded Vultures reveal about their dietary habits? *Science of the Total Environment, 728*(2020), 138836.

Schilthuizen, M. (2018). *Darwin in der Stadt. Die rasante Evolution der Tiere im Großstadtdschungel* [Darwin comes to town: How the urban jungle drives evolution]. DTV.

Schulze-Hagen, K. (2021). Niko Tinbergen und deutsche Ornithologen: Eine wechselseitige Inspiration [Niko Tinbergen and German ornithologists: A mutual inspiration]. *Vogelwarte, 59*, 7–20.

Schulze-Hagen, K., & Kaiser, G. (2019). *Die Vogel-WG. Die Heinroths, ihre 1000 Vögel und die Anfänge der Verhaltensforschung* [The bird commune. The Heinroths, their 1000 birds, and the beginnings of behavioral science]. Knesebeck.

Storch, V., Welsch, U., Wink, M. (2013). *Evolutionsbiologie* [Evolutionary biology] (3rd ed.). Springer.

Wink, M. (2014). *Ornithologie für Einsteiger* [Ornithology for beginners]. Springer-Spektrum.

Michael Wink is a full professor of Pharmaceutical Biology at Heidelberg University, where he has headed the Biology Department at the Institute of Pharmacy and Molecular Biotechnology since 1989. Since October 2019, he has been a senior professor. After studying biology and chemistry at the University of Bonn, he conducted research in Brunswick, Cologne, Munich, and Mainz. His fields of work range from phytochemistry, medicinal and poisonous plants, ornithology and conservation to systematics, phylogeny and evolutionary research. He is author/co-author of more than 30 books and over 1000 original papers. He is a visiting professor at universities in China, Thailand, Argentina and Mexico, as well as a member of various scientific advisory boards, editor of several journals, and recipient of several awards.

Chapter 5
Intelligence: Evolutionary Biological Foundations and Perspectives

Thomas W. Holstein

Abstract Although the term intelligence is now used in a wide variety of fields to explain the emergence of complex causalities, intelligence is understood here primarily as the ability of neural systems to solve problems in cognitive decision-making processes. Cognition and intelligent behavior are therefore primary objects, but not subjects, of chance-driven biological evolution. Recent work in neurobiology and comparative genomics has now shown how, starting from simple neural systems, forms capable of solving comparably complex problems in cognitive processes have evolved in all major groups of the animal kingdom. Although this cognition is based on the same basic cellular elements (neurons), it is realized in central nervous structures (brains), some of which have developed quite differently in animal evolution. By comparing the nervous systems of animals capable of higher intelligent sensory performance, the first common properties and principles are now becoming apparent, which are prerequisites for the emergence of higher intelligent systems (e.g., the density, but not number, of neuronal elements). Such common rules are probably also constraints in the development of artificial intelligent systems.

1 Introduction

The biological foundations of intelligence and our consciousness are one of the most exciting topics at the interface of biology and psychology, and they are of fundamental importance for the self-understanding of humans and our cognitive ability. For a long time, this topic was treated from an anthropocentric point of view, accepting that humans are a product of biological evolution, but at the same time claiming a special position for humans. An essential prerequisite for intelligence or intelligent cognition and intelligent behavior is without doubt the ability of individuals to develop a form of self-reflection and consciousness. For a long time, hominids, primates, and mammals in the broader sense had a unique selling point in

T. W. Holstein (✉)
Centre for Organismal Studies, University of Heidelberg, Heidelberg, Germany
e-mail: holstein@uni-heidelberg.de; https://www.cos.uni-heidelberg.de/index.php/t.holstein?l=#

R. M. Holm-Hadulla et al. (eds.), *Intelligence - Theories and Applications*,
https://doi.org/10.1007/978-3-031-04198-3_5

that it was assumed that only these animals had developed the corresponding correlate for consciousness in the form of the cerebral cortex during evolution.

In a September 2020 editorial in the American journal *Science*, two papers were presented under the title "Shared consciousness" (Nieder et al., 2020; Stacho et al., 2020), in which it was shown for the first time at the level of neuroanatomy and neuropsychology that in birds, when performing a complex "thinking task," neuronal responses are activated in the brain that correlate with the perception of stimuli of problem solving. Such activity appears to be the neural correlate and a marker of both consciousness and long-established cognitive abilities in these birds (Herculano-Houzel, 2020; Kabadayi et al., 2016; MacLean et al., 2014; Olkowicz et al., 2016).

This work raises a number of new questions that are fundamental to our understanding of the biological evolution of intelligence. They also pose the question of the special position of humans on a new basis: What are ultimately the molecular and cellular foundations of human intelligence? Does intelligence exist in other animal groups and on what principles is it based? If consciousness and intelligence have arisen multiple times in the animal kingdom in a convergent evolution, what is the significance of this for the development of "artificial intelligence"? This essay will attempt to provide an overview of recent work on the properties and evolution of neural systems that may provide answers to these questions.

2 Basics of Neuronal Cognition

The epitome of neural cognition is without doubt the human brain. Its immense complexity—it consists of a hundred billion neurons of an as yet unknown number of different types, each neuron capable of connecting to tens of thousands of other neurons—makes a holistic understanding of its functioning extremely difficult. However, the human brain has evolved from simpler forms in the more than 500 million years of its evolution. Much of current knowledge of the individual elements of our nervous system is therefore based on comparison with simpler and more accessible systems in invertebrates and vertebrates. For example, the large neurons of the marine snail *Aplysia* allow a detailed study of neuronal architecture and physiology during various forms of associative learning (Kandel et al., 2021). Additionally, the importance of ion channels in the formation of the action potential during excitation conduction was discovered in the giant axons of squid (Hodgkin & Huxley, 1952; Kandel et al., 2021). Although single neurons represent the functional units of nervous systems, they alone cannot explain the specific properties of neuronal systems; these always rely on multicellular circuits of neurons with emergent functional properties (Bosch et al., 2017). Understanding the earliest evolutionary examples of nervous systems is thus essential for understanding their function (Fig. 5.1).

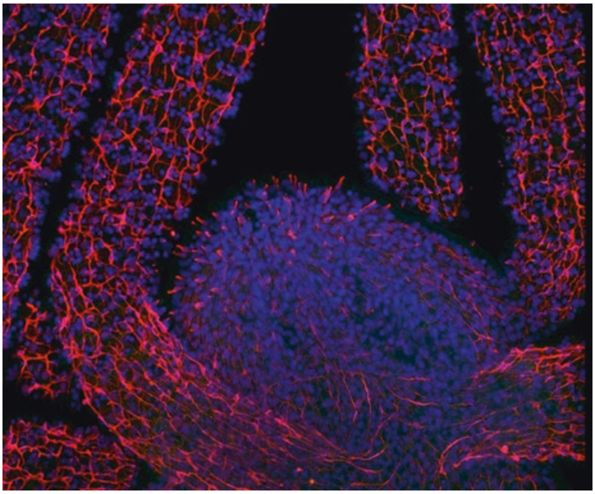

Fig. 5.1 A diffuse nervous network without brain and ganglia, like the nervous system of cnidarians, probably stood at the beginning of the evolution of nervous systems. The nerve network of the freshwater polyp *Hydra vulgaris*, shown by expression of a nerve-specific membrane protein (red) and cell nuclei stained with a DNA dye (DAPI) (blue). In *Hydra*, however, a high density of sensory neurons is established around the mouth opening (hypostome) of the polyp, which are important for the act of capture and feeding. There is a wide spectrum of different neurotransmitters expressed in subpopulations of neurons. Such simple neural networks are capable of complex behavioral patterns, such as the act of capture with cnidocytes or the different forms of locomotion (see Fig. 5.2), and are currently being studied in cellular and neurobiological terms. (Image © Bertulat & Holstein)

3 The First Nervous Systems

Nervous systems appeared very early in the evolution of animals and were certainly present before the emergence of bilaterally symmetrical animals—also known as Bilateria. Of the lineages that diverged prior to the radiation of Bilateria in the Cambrian ("Cambrian explosion"), nervous systems are present only in cnidarians (Cnidaria) and comb jellies (Ctenophora), but not in sponges (Chapman et al., 2010; Watanabe et al., 2009). The nervous systems of Cnidaria and Bilateria share many similarities, while there are differences in Ctenophora due to the limited number of neurotransmitters; also, their phylogenetic position is still open (Bosch et al., 2017; Moroz et al., 2014).

Cnidaria, which include medusae (jellyfish) and polyp-forming groups (hydras, anemones, corals), possess a nervous system that, unlike the nervous systems of the Bilateria, does not function as a centralized nervous system (CNS), but rather represents a diffuse neuronal network that operates without a brain or ganglia (Fig. 5.1). By comparing this simple neuronal system with the more complex systems, fundamental design principles of a CNS can be explored, including its contribution to higher neural functions such as consciousness and intelligent behavior (Bosch et al., 2017).

It is fascinating to see the complex behavioral patterns that Cnidaria already possess. The sophistication of their behavior was first recognized in the eighteenth century when Abraham Trembley described the locomotion of the freshwater polyp *Hydra* (Trembley, 1744) (Fig. 5.2).

However, medusae also possess a wide variety of behavioral patterns that are used not only for locomotion but also for prey capture and sexual reproduction. How all these behavioral patterns come about via a diffuse network of neurons is currently not understood at all (Bosch et al., 2017; Rentzsch et al., 2019). It is also entirely counterintuitive that in Cnidaria, the simple neural network exhibits sensory cells and organs comparable in complexity with the sensory outputs of vertebrates. For example, cnidarian cells are highly specialized neuronal cells that, with their nematocysts and ciliary mechano- and chemoreceptors, are among the most complex cell types in the animal kingdom (David et al., 2008; Holstein & Tardent, 1984; Nüchter et al., 2006), and cube jellyfish have evolved lens eyes, known only from the higher Bilateria, for orientation in space.

In recent years, in addition to the classic freshwater polyp *Hydra* and its related marine colonial forms (e.g., *Hydractinia echinata*), medusae (*Clytia hemispherica* and *Aurelia aurita*) and the sea anemone *Nematostella vectensis* have been studied in the laboratory and their genomes have been decoded (Chapman et al., 2010; Gold et al., 2019; Leclere et al., 2019; Putnam et al., 2007). As a result, several basal nervous systems are available for functional analyses, which can also be used to understand the origin of complex behaviors at the molecular level. The genomes and transcriptomes that have now been sequenced show that these behavioral patterns are based on an unexpectedly high genetic complexity of cnidarian neural networks. The diversity of synaptic proteins, small neurotransmitters, neuropeptides, as well as their processing machinery is as complex as that we know from "higher" animals, e.g., insects and vertebrates.

Thus, it can be concluded that the cellular and molecular repertoire of our nervous system evolved in the common ancestors of Cnidaria and Bilateria at a very early stage of evolution (>500 million years ago). Yet the primary function of the nervous system was probably "only" used for simple sensory and motor coordination. Nevertheless, given the complex behavioral patterns of these animals, it is currently debated to what extent these simple neural networks have properties beyond neural coordination, or whether higher neural functions require the centralization of the nervous system. The fact that the evolution of the CNS of Bilateria is closely linked to the existence of a second dorso-ventral body axis, which is still lacking in Cnidaria, suggests that certain circuits of the nervous system first evolved in Bilateria. Here, evolution led to ganglia and central nervous structures, which allowed for a higher neuronal density and thus a higher number of synaptic contacts.

The formation of a CNS can be understood as an evolutionary trend that occurred at the beginning of Bilateria evolution. Comparative genomic studies show commonalities in the ontogeny of the nervous system, including its central nervous elements, in all related groups of Bilateria, including the brain (Hirth et al., 2003;

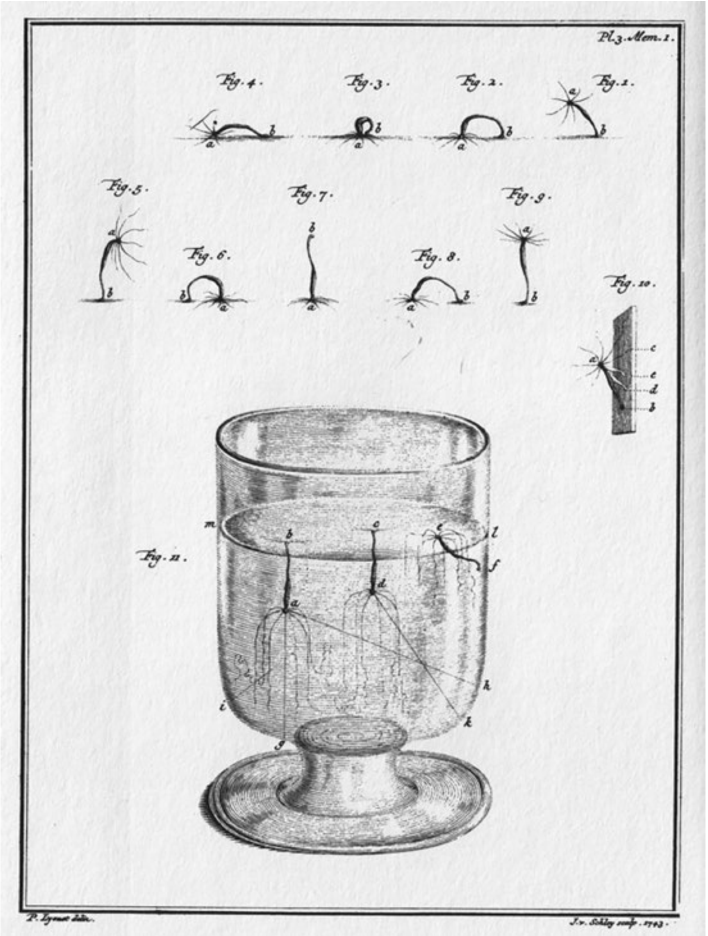

Fig. 5.2 The Geneva naturalist Abraham Trembley meticulously observed the freshwater polyp in its behavior and published his findings in 1744 in the influential book "*Mémoires pour servir à l'histoire d'un genre de polypes d'eau douce*." Plate 3 describes various patterns of movement of the hydras, which are about 1 cm long: One is a caterpillar-spinner-like locomotion (Figs. 1–4) in which the animal alternately contracts and stretches while the fixed aboral pole (b) follows the oral end with the tentacles and is thus lifted from one location to the next. The other movement involves summersaulting of the aboral end (foot) (Figs. 5–9). In addition, the animals may move vertically or in a vessel (Fig. 10) and attachment to the water surface (Fig. 11). Trembley was not only an "observational naturalist," but also a founder of experimental biology (discovery of regeneration in *Hydra*) with great impact on the philosophers of his time

Reichert, 2005). They fall into three major groups, the Deuterostomia, Lophotrochozoa, and Ecdysozoa. The Deuterostomia, which include vertebrates (vertebrates) as the largest group with humans, form the nervous system on the dorsal side (Notoneuralia), whereas Lophotrochozoa and Ecdysozoa form the

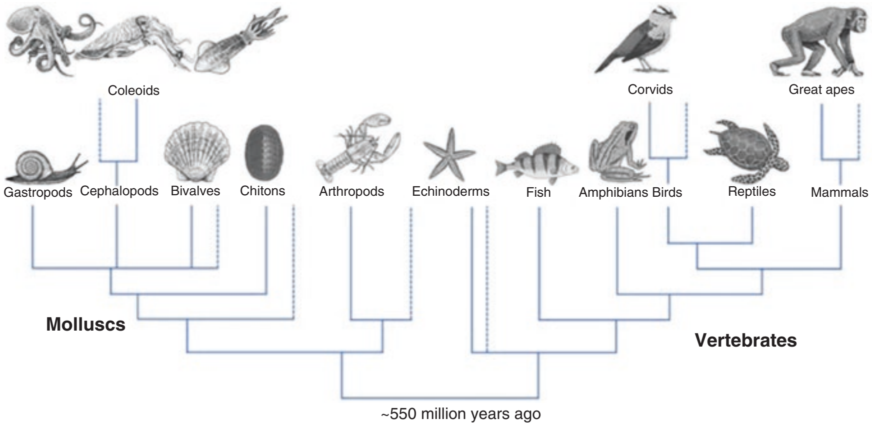

Fig. 5.3 Phylogenetic tree representing the evolutionary relationship between *cephalopods* (Cephalopoda) and corvids (Corvidae) and great apes (Hominidae). (Modified from: *Biological Reviews 96 (2021) 162–178* © 2020 *The Authors. Biological Reviews published by John Wiley & Sons Ltd on behalf of Cambridge Philosophical Society. Image sources:* © *CCBY-SA: snail, echinoderm, chiton*; © CCBY-NC-ND*: octopus*; © jenesesimre, *stock.adobe.com*: *octopus, squid, arthropod, clam;* © artbalitskiy, *stock.adobe.com*: *monkey, corvid, fish, amphibian, reptile*)

nervous system on the ventral side (Gastroneuralia). Recent findings suggest that forms with a CNS have evolved independently (convergently) in the three major groups, which are capable of higher neuronal outputs and thus intelligent behavior according to behavioral criteria (Roth, 2015; Roth & Dicke, 2005, 2012) (Fig. 5.3).

4 Cognition in Invertebrates

Insects possess the most complex brains of the Ecdysozoa. They belong to the arthropods, whose nervous system is derived from simple progenitors with an oral nerve ring and ventral nerve cords containing ganglia. The tripartite brain has so-called “mushroom bodies” (*corpora pedunculata*) in its anterior part, which occupy half of the brain volume in honeybees and whose neuronal density is an order of magnitude greater than in vertebrates (Reichert, 2005; Roth, 2015) (Strausfeld & Hirth, 2013). The region has been identified as a substrate for the evolution of cognitive and social functions and has an impressive repertoire and flexibility of behavioral patterns for foraging, spatial orientation, and social interaction (Roth, 2015). Bees are also characterized by their great learning behavior and appear to be capable of building cognitive maps for spatial orientation that can be retrieved in a context-dependent manner (Roth, 2015), although this is still under debate (Cruse & Wehner, 2011; Wehner & Menzel, 1969).

The most complex brains of the Lophotrochozoa—and of all animals outside of vertebrates—are found in the cephalopod molluscs, including octopuses (Octopoda), squids (Theutidae), and cuttlefish (Sepiida) (Albertin et al., 2015; Wanninger & Wollesen, 2019). As a member of the large group of molluscs (Mollusca), which also includes bivalves and gastropods, their nervous systems are derived from simple forms with an oral nerve ring and ganglia-containing ventral nerve cords, as found in annelids (polychaete). The nervous system of squid contains approximately 550 million neurons, of which approx. 90% are in the arms and optic nerves and 10% are in the brain proper. The brain is divided into a ventral motor section and a dorsal section, to which sensory information processing and higher cognitive functions are attributed (Albertin et al., 2015; Roth, 2015; Shomrat et al., 2008). The vertical lobe of an octopus brain is its most complex part and key structure for the circuits involved in learning and memory processes (Albertin et al., 2015; Shomrat et al., 2008; Young et al., 1971). It contains more than half of the neurons in the brain, with approximately 26 million neurons (Roth, 2015). It consists of two types of neurons: interneurons that can form "*en passant*" synapses to primarily visual afferents and projection neurons that connect to the subvertical lobe. This creates a highly ordered network with millions of intersecting fibers.

In the recently published first description of the genome of *Octopus bimaculoides*, it was shown that the molecular basis of this highly complex brain is based, among other things, on neuronal adhesion proteins that are responsible for the formation of synaptic contacts between neurons (Albertin et al., 2015). In the *Octopus* genome, 168 genes encoding for cell adhesion proteins (protocadherins) are present. They result from tandem gene duplication and an expansion of this gene family that is primarily expressed in neural tissue. The function of protocadherins has been studied primarily in mammals, where they are required for neuronal development and survival as well as synaptic specificity; however, they arise here by complex splicing rather than gene duplication. The expression of protocadherins in squid neural tissues suggests a central role for these genes in establishing and maintaining the organization of the cephalopod nervous system as known from mammals (Albertin et al., 2015).

The highly complex molecular and morphological structure of octopus brains enables us to understand why so many "intelligent" behaviors have been described in these animals. For example, an "*Octopus* is not only good at remembering where tasty food can be found, but after a journey far from home, it often returns home by the shortest route it had never taken before." (Roth, 2015). As with bees, there is debate as to whether squids have a "mental map" (Roth, 2015) and the extent to which they are capable of "learning by observation" (Fiorito & Chichery, 1995; Fiorito & Scotto, 1992; Roth, 2015).

However, these reports of intelligent behavior in squid have now taken on a new quality, as it has been shown that squids are also capable of exercising self-control in a reward-delay task (Schnell et al., 2021a, b; Schnell & Clayton, 2019). The ability to overcome immediate gratification in favor of a better but delayed reward is considered an important cognitive skill for effective decision making, goal-directed behavior, and future planning (Mischel & Underwood, 1974; Santos & Rosati, 2015; Schnell et al., 2021a, b; Schnell & Clayton, 2019). In humans, the ability to exercise self-control has been linked to children's cognitive performance: children who were able to delay a reward longer,[1] also performed better on intellectual tasks (Mischel, 2015; Mischel et al., 1989). To test self-control in squid, Schnell and colleagues gave the animals a task that also measured an individual's ability to forgo immediate reward (Schnell et al., 2021a, b). Squid maintained delay times for up to 50–130 s. To test learning performance, squid had to learn to associate the reward with one of two stimuli; they then had to learn to associate the reward with the alternative stimulus. Again, squid that were able to delay their reward longer than others had better learning performance (Schnell et al., 2021a, b). The work showed that squid can tolerate delays in order to obtain food of higher quality or quantity, which is ultimately comparable to the situation in mammals (Schnell et al., 2021a, b).

5 Cognition in Vertebrates

Humans (*Homo* sp.) belong to a genus that is member of the family of great apes (Hominidae) and thus to mammals (Mammalia). The study of complex cognition has traditionally been limited to hominids and related groups within primates, as these have been considered the pinnacle of cognitive complexity, although there has been increasing evidence that there are other mammals, as well as birds (Aves), that possess brains capable of cognitive performance comparable to that of primates (MacLean et al., 2014; Olkowicz et al., 2016). Examples include cetaceans (Fox et al., 2017; Marino, 2002), elephants (Plotnik et al., 2006, 2011), or parrots (Pepperberg, 2006; Pepperberg et al., 2013) and corvids (Boeckle & Bugnyar, 2012; Emery & Clayton, 2004). The fact that corvids possess cognitive abilities equivalent to those of monkeys (Clayton & Emery, 2005; Emery & Clayton, 2005; Güntürkün & Bugnyar, 2016; Kabadayi et al., 2016) has therefore raised the question of whether complex cognition has evolved repeatedly and independently in vertebrates (Roth, 2015).

Mammalia and Aves diverged into two distinct groups of amniotes[2] approximately 300 million years ago, and their brains—like the nervous systems of all vertebrates—can be traced back to the simplest precursors of chordates 550 million years ago (Fig. 5.3). According to general doctrine, however, there are fundamental differences in brain anatomy and neuroarchitecture between apes and corvids (Jarvis et al., 2005). According to this view, the mantle layer (pallium) of the cerebrum in birds does not possess layering as in mammals (this powerful layering has earned the mammalian pallium the name "cerebral cortex"), and therefore birds would not possess a cerebral cortex (Güntürkün & Bugnyar, 2016;

[1] Children were presented with one marshmallow and given a choice—eat it immediately or wait to get two later. The experiment also became known as the Marshmallow Test (Walter Mischel 2014, Settlers, ISBN 9783827500434).

[2] Amniotes are terrestrial vertebrates that can reproduce independently of water through embryonic shells, whereas amphibians depend on it for embryonic development and produce tadpoles as larval stages postembryonically.

Herculano-Houzel, 2020). However, this assumption of an absent cerebral cortex has been challenged because, like our cerebral cortex, the pallium of birds also derives embryonically from the same section of the developing brain with all molecular markers, and it has a comparably high number and density of neurons (Güntürkün & Bugnyar, 2016; Herculano-Houzel, 2020; Puelles et al., 2013). In the new work, it is now shown that the avian pallium has a similar neuronal organization and layering as the mammalian cortex and has neurons (Stacho et al., 2020) that can neurophysiologically represent what is perceived (Nieder et al., 2020), which is a hallmark of consciousness (Herculano-Houzel, 2020).

Therefore, an intriguing question is to what extent within vertebrate cognition and the capacity for consciousness already existed in the common ancestor of birds and mammals (Bshary & Brown, 2014; Herculano-Houzel, 2020; Nieder et al., 2020). Although the evolution of squid and comparison with other animal groups suggests that there was convergent evolution of higher cognition and consciousness (Roth, 2015), there do appear to be certain structural and embryological commonalities within vertebrates that resulted in the evolution of neuronal structures with particularly high neuronal density being built only in certain regions, which then enabled the emergence of higher intelligent systems. Therefore, in addition to birds, the biological foundations of cognition in primates/hominids, the group of mammals to which we humans belong, will be conclusively addressed.

6 Hominid Cognition

It has long been assumed that the high cognitive performance and intelligence that characterize hominids and humans are closely related to, or even explained by, the size and complexity of the brain and cerebral cortex (*cortex cerebri*) (Fig. 5.3). Indeed, within hominids there has been an extremely rapid increase in brain size since the split of the great apes and genus *Homo* in the late Miocene 6–7 million years ago (Harrison, 2010), particularly in human evolution, while brain size has changed less among the different great ape groups within hominids.

The large increase in size of the human brain was accompanied by significant restructuring of the digestive system and feeding and social behaviors (Fonseca-Azevedo & Herculano-Houzel, 2012; Roth & Dicke, 2005, 2012).

Repeated attempts have been made to correlate high cognitive performance in mammals in general with brain size. In 2005, Roth and Dicke determined the available data on brain size in various mammals and examined the correlation to brain cognitive performance (Roth & Dicke, 2005, 2012). This showed that while absolute brain size can vary by up to five orders of magnitude within mammals (ranging in weight from 0.1 g for the smallest brains in insectivores and bats to 9000 g in large whales), the human brain is far from the largest (weighing slightly less than 1.35 kg). This is also true when considering the relative size of the brain (brain size/

body size), thereby compensating for allometric effects,[3] again hominids are in the middle range (Roth & Dicke, 2005, 2012). The data therefore do not allow for a simple correlation between brain size and cognitive performance.

A clearer picture emerges for the structures of the cortex relevant for cognition, where the most neurons among recent primates are found in humans (Sousa et al., 2017). The neurobiological substrate of general intelligence in mammals is considered to be the frontal lobe (prefrontal cortex) located at the front of the brain (Duncan et al., 2000). It is directly involved in linking sensory information to the cognitive-mental processes of thinking, action planning, and decision making (Roth & Dicke, 2005, 2012). Although the human prefrontal cortex is particularly large (Roth & Dicke, 2005, 2012), recent comparative studies in primates have fundamentally questioned the disproportionate size of the human prefrontal cortex (Roth & Dicke, 2005, 2012; Semendeferi et al., 2002), an issue that remains the subject of current research (Hayashi et al., 2021).

Since neither absolute nor relative brain size is a unique feature of the human brain, the question arises as to what biological properties of the brain distinguish humans from their closest recent hominid relatives, the chimpanzees (*Pan troglodytes*) and pygmy chimpanzees or bonobos (*Pan paniscus*). Thus, the view is gaining ground that the key to the unique capabilities of the human brain is expressed less in its absolute or relative size, or even in the number of neurons and glia, but rather in more subtle components such as a greater diversity of neuronal cell types or more complex patterns of neuronal connectivity (Sousa et al., 2017). Moreover, these changes must be evolutionarily young, i.e., they must have started at the earliest with the strong brain development of hominids in the early Miocene (15–18 million years ago) and at the latest with the split of the genus *Homo* from the rest of the hominids, the great apes, in the late Miocene 6–7 million years ago.

At this point, comparative genomic studies have been crucial to a better understanding of possible factors in brain evolution within mammals. Direct comparison of the now fully sequenced great ape genomes (Chimpanzee & Analysis, 2005; Kronenberg et al., 2018; Locke et al., 2011; Mao et al., 2021; Scally et al., 2012) with that of humans allows the identification of relevant neuronal genes that are exclusive to humans and that have newly formed during this time window, e.g., through gene duplication. This approach has been used to identify primate-specific genes that are particularly active in the neural stem and progenitor cells of the developing neocortex (Florio et al., 2018). The number of strictly human-specific genes is limited ($n = 15$), have emerged within the last 6–7 million years, and contain regulatory genes involved in neuronal proliferation and expansion of the neocortex (Florio et al., 2015, 2018). Other neocortex-specific genes present in other primates

[3] Allometry relates organ size to body size; the brain follows a power function with an exponent of 0.6–0.8, meaning that as body size increases, brains become larger in absolute terms but smaller in relative terms (Roth, G., and U. Dicke. 2005. Evolution of the brain and intelligence. Trends Cogn. Sci. 9:250–257, Roth, G., and U. Dicke. 2012. Evolution of the brain and intelligence in primates. Prog Brain Res. 195:413–430).

or mammals were higher in number (n = 3458) but also contribute to neocortical development (Florio et al., 2018).

Of particular interest here is the *SLIT-ROBO GTPase 2* (*SRGAP2*) gene, whose expression is also enriched in the developing neocortex (Charrier et al., 2012; Dennis et al., 2012). It is known that SRGAP2 is involved in brain development (Guerrier et al., 2009) and that humans carry at least three similar copies of the gene, whereas non-human primates carry only one. Humans have been shown to carry four non-identical copies (termed A–D) of *SRGAP2* at different locations on chromosome 1 (Geschwind & Konopka, 2012). By comparing the gene sequences to those of the orangutan and chimpanzee *SRGAP2 genes*, the authors estimated that *SRGAP2* was duplicated in the human lineage approximately 3.4 million years ago, resulting in *SRGAP2A* and *SRGAP2B* (Geschwind & Konopka, 2012).

Further duplications of *SRGAP2B* led to *SRGAP2C* approximately 2.4 million years ago and to *SRGAP2D* approx. 1 million years ago, and *SRGAP2C* in particular may have played an important role 2–3 million years ago when human cognition evolved (Geschwind & Konopka, 2012). A further study shed light on the mechanism of the *SRGAP2 gene* (Charrier et al., 2012). The formation of dendritic protrusions (*spines*) on the surface of neurons is essential for the formation of synaptic contacts. Here, SRGAP2A has been shown to promote the formation of spines and slow the migration of neurons within the developing cerebral cortex, while the human-specific SRGAP2C promotes the formation of more spines.

This results in a higher density of *spines* and a slowdown in cortical development, allowing for greater brain plasticity, i.e., the ability to change neuronal connections in response to new experiences (Geschwind & Konopka, 2012). Duplication of *SRGAP2C* has also been found in Neanderthals and Denisova humans. Interestingly, the *FOXP2* gene, which is associated with the establishment of some aspects of our brain's language ability as well as language disorders, also has the same mutations in Neanderthals and humans that the great apes lack (Krause et al., 2007).

7 From Homo Sapiens Intelligence to Artificial Intelligence?

The aim of this work was to show how the simplest stages of a neural network gave rise to complex nervous systems that are very likely convergent with each other in a wide variety of animal groups over the >600–500 million years of evolution. Humans therefore no longer appear to be the only species to possess intelligence. However, a comparison of the different systems shows that the high cognitive performances that enable intelligent behavior are always tied to a specific environment and context. These contexts are at the same time linked to millions of years of evolution of biological "cognition systems." Artificial intelligence is therefore only conceivable as an extension of human intelligence, albeit with the inclusion of all the sophistication that made the emergence of higher cognition possible in evolution.

Acknowledgements Many thanks to Rainer M. Holm-Hadulla, who gave the impulse for this work and enabled me to look beyond the "edge of my nose" of our research on the nervous system of the Cnidaria.

References

Albertin, C. B., Simakov, O., Mitros, T., Wang, Z. Y., Pungor, J. R., Edsinger-Gonzales, E., Brenner, S., Ragsdale, C. W., & Rokhsar, D. S. (2015). The octopus genome and the evolution of cephalopod neural and morphological novelties. *Nature, 524*, 220–224.

Boeckle, M., & Bugnyar, T. (2012). Long-term memory for affiliates in ravens. *Current Biology, 22*, 801–806.

Bosch, T. C. G., Klimovich, A., Domazet-Loso, T., Grunder, S., Holstein, T. W., Jekely, G., Miller, D. J., Murillo-Rincon, A. P., Rentzsch, F., Richards, G. S., Schroder, K., Technau, U., & Yuste, R. (2017). Back to the basics: Cnidarians start to fire. *Trends in Neurosciences, 40*, 92–105.

Bshary, R., & Brown, C. (2014). Fish cognition. *Current Biology, 24*, R947–R950.

Chapman, J. A., Kirkness, E. F., Simakov, O., Hampson, S. E., Mitros, T., Weinmaier, T., Rattei, T., Balasubramanian, P. G., Borman, J., Busam, D., Disbennett, K., Pfannkoch, C., Sumin, N., Sutton, G. G., Viswanathan, L. D., Walenz, B., Goodstein, D. M., Hellsten, U., Kawashima, T., … Steele, R. E. (2010). The dynamic genome of hydra. *Nature, 464*, 592–596.

Charrier, C., Joshi, K., Coutinho-Budd, J., Kim, J. E., Lambert, N., de Marchena, J., Jin, W. L., Vanderhaeghen, P., Ghosh, A., Sassa, T., & Polleux, F. (2012). Inhibition of SRGAP2 function by its human-specific paralogs induces neoteny during spine maturation. *Cell, 149*, 923–935.

Chimpanzee, S., & Analysis, C. (2005). Initial sequence of the chimpanzee genome and comparison with the human genome. *Nature, 437*, 69–87. https://doi.org/10.1038/nature04072

Clayton, N., & Emery, N. (2005). Corvid cognition. *Current Biology, 15*, R80–R81.

Cruse, H., & Wehner, R. (2011). No need for a cognitive map: Decentralized memory for insect navigation. *PLoS Computational Biology, 7*, e1002009.

David, C. N., Ozbek, S., Adamczyk, P., Meier, S., Pauly, B., Chapman, J., Hwang, J. S., Gojobori, T., & Holstein, T. W. (2008). Evolution of complex structures: Minicollagens shape the cnidarian nematocyst. *Trends in Genetics, 24*, 431–438.

Dennis, M. Y., Nuttle, X., Sudmant, P. H., Antonacci, F., Graves, T. A., Nefedov, M., Rosenfeld, J. A., Sajjadian, S., Malig, M., Kotkiewicz, H., Curry, C. J., Shafer, S., Shaffer, L. G., de Jong, P. J., Wilson, R. K., & Eichler, E. E. (2012). Evolution of human-specific neural SRGAP2 genes by incomplete segmental duplication. *Cell, 149*, 912–922.

Duncan, J., Seitz, R. J., Kolodny, J., Bor, D., Herzog, H., Ahmed, A., Newell, F. N., & Emslie, H. (2000). A neural basis for general intelligence. *Science, 289*, 457–460.

Emery, N. J., & Clayton, N. S. (2004). The mentality of crows: Convergent evolution of intelligence in corvids and apes. *Science, 306*, 1903–1907.

Emery, N. J., & Clayton, N. S. (2005). Evolution of the avian brain and intelligence. *Current Biology, 15*, R946–R950.

Fiorito, G., & Chichery, R. (1995). Lesions of the vertical lobe impair visual discrimination learning by observation in Octopus vulgaris. *Neuroscience Letters, 192*, 117–120.

Fiorito, G., & Scotto, P. (1992). Observational learning in Octopus vulgaris. *Science, 256*, 545–547.

Florio, M., Albert, M., Taverna, E., Namba, T., Brandl, H., Lewitus, E., Haffner, C., Sykes, A., Wong, F. K., Peters, J., Guhr, E., Klemroth, S., Prufer, K., Kelso, J., Naumann, R., Nusslein, I., Dahl, A., Lachmann, R., Paabo, S., & Huttner, W. B. (2015). Human-specific gene ARHGAP11B promotes basal progenitor amplification and neocortex expansion. *Science, 347*, 1465–1470.

Florio, M., Heide, M., Pinson, A., Brandl, H., Albert, M., Winkler, S., Wimberger, P., Huttner, W. B., & Hiller, M. (2018). Evolution and cell-type specificity of human-specific genes preferentially expressed in progenitors of fetal neocortex. *eLife, 7*, e32332.

Fonseca-Azevedo, K., & Herculano-Houzel, S. (2012). Metabolic constraint imposes tradeoff between body size and number of brain neurons in human evolution. *Proceedings of the National Academy of Sciences, 109*, 18571–18576.

Fox, K. C. R., Muthukrishna, M., & Shultz, S. (2017). The social and cultural roots of whale and dolphin brains. *Nature Ecology & Evolution, 1*, 1699–1705.

Geschwind, D. H., & Konopka, G. (2012). Neuroscience: Genes and human brain evolution. *Nature, 486*, 481–482.

Gold, D. A., Katsuki, T., Li, Y., Yan, X., Regulski, M., Ibberson, D., Holstein, T., Steele, R. E., Jacobs, D. K., & Greenspan, R. J. (2019). The genome of the jellyfish Aurelia and the evolution of animal complexity. *Nature Ecology and Evolution, 3*, 96–104.

Guerrier, S., Coutinho-Budd, J., Sassa, T., Gresset, A., Jordan, N. V., Chen, K., Jin, W. L., Frost, A., & Polleux, F. (2009). The F-BAR domain of srGAP2 induces membrane protrusions required for neuronal migration and morphogenesis. *Cell, 138*, 990–1004.

Güntürkün, O., & Bugnyar, T. (2016). Cognition without cortex. *Trends in Cognitive Sciences, 20*, 291–303.

Harrison, T. (2010). Anthropology. Apes among the tangled branches of human origins. *Science, 327*, 532–534.

Hayashi, T., Hou, Y., Glasser, M. F., Autio, J. A., Knoblauch, K., Inoue-Murayama, M., Coalson, T., Yacoub, E., Smith, S., Kennedy, H., & Van Essen, D. C. (2021). The nonhuman primate neuroimaging and neuroanatomy project. *NeuroImage, 229*, 117726.

Herculano-Houzel, S. (2020). Birds do have a brain cortex-and think. *Science, 369*, 1567–1568.

Hirth, F., Kammermeier, L., Frei, E., Walldorf, U., Noll, M., & Reichert, H. (2003). An urbilaterian origin of the tripartite brain: Developmental genetic insights from Drosophila. *Development, 130*, 2365–2373.

Hodgkin, A. L., & Huxley, A. F. (1952). Propagation of electrical signals along giant nerve fibers. *Proceedings of the Royal Society of London - Series B: Biological Sciences, 140*, 177–183.

Holstein, T., & Tardent, P. (1984). An ultrahigh-speed analysis of exocytosis: Nematocyst discharge. *Science, 223*, 830–833.

Jarvis, E. D., Güntürkün, O., Bruce, L., Csillag, A., Karten, H., Kuenzel, W., Medina, L., Paxinos, G., Perkel, D. J., Shimizu, T., Striedter, G., Wild, J. M., Ball, G. F., Dugas-Ford, J., Durand, S. E., Hough, G. E., Husband, S., Kubikova, L., Lee, D. W., … C. Avian Brain Nomenclature. (2005). Avian brains and a new understanding of vertebrate brain evolution. *Nature Reviews. Neuroscience, 6*, 151–159.

Kabadayi, C., Taylor, L. A., von Bayern, A. M., & Osvath, M. (2016). Ravens, New Caledonian crows and jackdaws parallel great apes in motor self-regulation despite smaller brains. *Royal Society Open Science, 3*, 160104.

Kandel, E. R., Koester, J. D., Mack, S. H., & Siegelbaum, S. A. (2021). *Principles of neural science* (6th ed.). McGraw-Hill Education.

Krause, J., Lalueza-Fox, C., Orlando, L., Enard, W., Green, R. E., Burbano, H. A., Hublin, J. J., Hanni, C., Fortea, J., de la Rasilla, M., Bertranpetit, J., Rosas, A., & Paabo, S. (2007). The derived FOXP2 variant of modern humans was shared with Neandertals. *Current Biology, 17*, 1908–1912.

Kronenberg, Z. N., Fiddes, I. T., Gordon, D., Murali, S., Cantsilieris, S., Meyerson, O. S., Underwood, J. G., Nelson, B. J., Chaisson, M. J. P., Dougherty, M. L., Munson, K. M., Hastie, A. R., Diekhans, M., Hormozdiari, F., Lorusso, N., Hoekzema, K., Qiu, R., Clark, K., Raja, A., … Eichler, E. E. (2018). High-resolution comparative analysis of great ape genomes. *Science, 360*, eaar6343.

Leclere, L., Horin, C., Chevalier, S., Lapebie, P., Dru, P., Peron, S., Jager, M., Condamine, T., Pottin, K., Romano, S., Steger, J., Sinigaglia, C., Barreau, C., Quiroga Artigas, G., Ruggiero, A., Fourrage, C., Kraus, J. E. M., Poulain, J., Aury, J. M., … Copley, R. R. (2019). The genome of the jellyfish Clytia hemisphaerica and the evolution of the cnidarian life-cycle. *Nature Ecology & Evolution, 3*, 801–810.

Locke, D. P., Hillier, L. W., Warren, W. C., Worley, K. C., Nazareth, L. V., Muzny, D. M., Yang, S. P., Wang, Z., Chinwalla, A. T., Minx, P., Mitreva, M., Cook, L., Delehaunty, K. D., Fronick, C., Schmidt, H., Fulton, L. A., Fulton, R. S., Nelson, J. O., Magrini, V., et al. (2011). Comparative and demographic analysis of orangutan genomes. *Nature, 469*, 529–533.

MacLean, E. L., Hare, B., Nunn, C. L., Addessi, E., Amici, F., Anderson, R. C., Aureli, F., Baker, J. M., Bania, A. E., Barnard, A. M., Boogert, N. J., Brannon, E. M., Bray, E. E., Bray, J., Brent, L. J., Burkart, J. M., Call, J., Cantlon, J. F., Cheke, L. G., … Zhao, Y. (2014). The evolution of self-control. *Proceedings of the National Academy of Sciences of the United States of America, 111*, E2140–E2148.

Mao, Y., Catacchio, C. R., Hillier, L. W., Porubsky, D., Li, R., Sulovari, A., Fernandes, J. D., Montinaro, F., Gordon, D. S., Storer, J. M., Haukness, M., Fiddes, I. T., Murali, S. C., Dishuck, P. C., Hsieh, P., Harvey, W. T., Audano, P. A., Mercuri, L., Piccolo, I., … Eichler, E. E. (2021). A high-quality bonobo genome refines the analysis of hominid evolution. *Nature, 594*, 77–81.

Marino, L. (2002). Convergence of complex cognitive abilities in cetaceans and primates. *Brain, Behavior and Evolution, 59*, 21–32.

Mischel, W., & Underwood, B. (1974). Instrumental ideation in delay of gratification. *Child Development, 45*, 1083–1088.

Mischel, W. (2015). *The Marshmallow test: Why self-control is the engine of success*. Little, Brown.

Mischel, W., Shoda, Y., & Rodriguez, M. I. (1989). Delay of gratification in children. *Science, 244*, 933–938.

Moroz, L. L., Kocot, K. M., Citarella, M. R., Dosung, S., Norekian, T. P., Povolotskaya, I. S., Grigorenko, A. P., Dailey, C., Berezikov, E., Buckley, K. M., Ptitsyn, A., Reshetov, D., Mukherjee, K., Moroz, T. P., Bobkova, Y., Yu, F., Kapitonov, V. V., Jurka, J., Bobkov, Y. V., … Kohn, A. B. (2014). The ctenophore genome and the evolutionary origins of neural systems. *Nature, 510*, 109–114.

Nieder, A., Wagener, L., & Rinnert, P. (2020). A neural correlate of sensory consciousness in a corvid bird. *Science, 369*, 1626–1629.

Nüchter, T., Benoit, M., Engel, U., Ozbek, S., & Holstein, T. W. (2006). Nanosecond-scale kinetics of nematocyst discharge. *Current Biology, 16*, R316–R318.

Olkowicz, S., Kocourek, M., Lucan, R. K., Portes, M., Fitch, W. T., Herculano-Houzel, S., & Nemec, P. (2016). Birds have primate-like numbers of neurons in the forebrain. *Proceedings of the National Academy of Sciences of the United States of America, 113*, 7255–7260.

Pepperberg, I. M. (2006). Grey parrot numerical competence: A review. *Animal Cognition, 9*, 377–391.

Pepperberg, I. M., Koepke, A., Livingston, P., Girard, M., & Hartsfield, L. A. (2013). Reasoning by inference: Further studies on exclusion in grey parrots (Psittacus erithacus). *Journal of Comparative Psychology, 127*, 272–281.

Plotnik, J. M., de Waal, F. B., & Reiss, D. (2006). Self-recognition in an Asian elephant. *Proceedings of the National Academy of Sciences of the United States of America, 103*, 17053–17057.

Plotnik, J. M., Lair, R., Suphachoksahakun, W., & de Waal, F. B. (2011). Elephants know when they need a helping trunk in a cooperative task. *Proceedings of the National Academy of Sciences of the United States of America, 108*, 5116–5121.

Puelles, L., Harrison, M., Paxinos, G., & Watson, C. (2013). A developmental ontology for the mammalian brain based on the prosomeric model. *Trends in Neurosciences, 36*, 570–578.

Putnam, N. H., Srivastava, M., Hellsten, U., Dirks, B., Chapman, J., Salamov, A., Terry, A., Shapiro, H., Lindquist, E., Kapitonov, V. V., Jurka, J., Genikhovich, G., Grigoriev, I. V., Lucas, S. M., Steele, R. E., Finnerty, J. R., Technau, U., Martindale, M. Q., & Rokhsar, D. S. (2007). Sea anemone genome reveals ancestral eumetazoan gene repertoire and genomic organization. *Science, 317*, 86–94.

Reichert, H. (2005). A tripartite organization of the urbilaterian brain: Developmental genetic evidence from Drosophila. *Brain Research Bulletin, 66*, 491–494.

Rentzsch, F., Juliano, C., & Galliot, B. (2019). Modern genomic tools reveal the structural and cellular diversity of cnidarian nervous systems. *Current Opinion in Neurobiology, 56*, 87–96.

Roth, G. (2015). Convergent evolution of complex brains and high intelligence. *Philosophical Transactions of the Royal Society B, 370*, 20150049.
Roth, G., & Dicke, U. (2005). Evolution of the brain and intelligence. *Trends in Cognitive Sciences, 9*, 250–257.
Roth, G., & Dicke, U. (2012). Evolution of the brain and intelligence in primates. *Progress in Brain Research, 195*, 413–430.
Santos, L. R. & Rosati, A. G. (2015). The evolutionary roots of human decision making. *Annual review of psychology 66*, 321–347.
Scally, A., Dutheil, J. Y., Hillier, L. W., Jordan, G. E., Goodhead, I., Herrero, J., Hobolth, A., Lappalainen, T., Mailund, T., Marques-Bonet, T., McCarthy, S., Montgomery, S. H., Schwalie, P.-C., Tang, Y. A., Ward, M. C., Xue, Y., Yngvadottir, B., Alkan, C., Andersen, L. N., … Durbin, R. (2012). Insights into hominid evolution from the gorilla genome sequence. *Nature, 483*, 169–175.
Schnell, A. K., & Clayton, N. S. (2019). Cephalopod cognition. *Current Biology, 29*, R726–R732.
Schnell, A. K., Amodio, P., Boeckle, M., & Clayton, N. S. (2021a). How intelligent is a cephalopod? Lessons from comparative cognition. *Biological Reviews of the Cambridge Philosophical Society, 96*, 162–178.
Schnell, A. K., Boeckle, M., Rivera, M., Clayton, N. S., & Hanlon, R. T. (2021b). Cuttlefish exert self-control in a delay of gratification task. *Proceedings of the Biological Sciences, 288*, 20203161.
Semendeferi, K., Lu, A., Schenker, N., & Damasio, H. (2002). Humans and great apes share a large frontal cortex. *Nature Neuroscience, 5*, 272–276.
Shomrat, T., Zarrella, I., Fiorito, G., & Hochner, B. (2008). The octopus vertical lobe modulates short-term learning rate and uses LTP to acquire long-term memory. *Current Biology, 18*, 337–342.
Sousa, A. M. M., Meyer, K. A., Santpere, G., Gulden, F. O., & Sestan, N. (2017). Evolution of the human nervous system function, structure, and development. *Cell, 170*, 226–247.
Stacho, M., Herold, C., Rook, N., Wagner, H., Axer, M., Amunts, K., & Güntürkün, O. (2020). A cortex-like canonical circuit in the avian forebrain. *Science, 369*, eabc5534.
Strausfeld, N. J., & Hirth, F. (2013). Deep homology of arthropod central complex and vertebrate basal ganglia. *Science, 340*, 157–161.
Trembley, A. (1744). *Mémoires pour servir à l'histoire d'un genre de polypes d'eau douce à bras en forme de cornes*. J. & H. Verbeek.
Wanninger, A., & Wollesen, T. (2019). The evolution of molluscs. *Biological Reviews of the Cambridge Philosophical Society, 94*, 102.
Watanabe, H., Fujisawa, T., & Holstein, T. W. (2009). Cnidarians and the evolutionary origin of the nervous system. *Development, Growth & Differentiation, 51*, 167–183.
Wehner, R., & Menzel, R. (1969). Homing in the ant Cataglyphis bicolor. *Science, 164*, 192–194.
Young, J. Z., Young, J. Z., & Boycott, B. B. (1971). *The anatomy of the nervous system of octopus vulgaris*. Clarendon Press.

Thomas W. Holstein studied biology at the University of Vienna (1973–1980) (Dr. phil.). Afterwards he was at the University of Zürich (1980–1983) and University of Munich (1983–1993) (Dr. rer. nat. habil). He was associate professor at the University of Frankfurt (1993–1998) and full professor at the Technical University of Darmstadt (1998–2004). He declined offers to the Universities of Karlsruhe and Vienna, and joined the University of Heidelberg in 2004, where he has been teaching and researching ever since. Here, he was managing Director of the Zoological Institute (2004–2011), Dean of the Faculty of Biosciences (2007–2012), Fellow at the Heidelberg Marsilius-Kolleg (2011–2014), and President of the Heidelberg Academy of Sciences (2015–2020). He is a member of the DFG's SFB 1324, who's spokesperson he was in the first funding period (2017–2021). His field of work is molecular cell and developmental biology with a focus on questions in evolutionary biology. With his research group, he works on stem cells and the nervous system of the freshwater polyp *Hydra* and the sea anemone *Nematostella*.

Chapter 6
When Intelligence Is Impaired

Gudrun A. Rappold

Abstract The past decade has seen a wealth of discoveries that have led to the elucidation and understanding of neurodevelopmental disorders, including mental retardation and autism spectrum disorder. These successes were made possible by methodological advances in array diagnostics and next-generation sequencing. As a result, the causes of more than half of all neurodevelopmental disorders could be identified. Early detection of these profound developmental disorders in the early stages of brain development is of great importance in order to initiate effective treatment yes. A deeper understanding of the neurobiological processes of the identified genes and their metabolic pathways is also necessary to better understand the development and function of neuronal networks and circuitry.

1 David and the FOXP1 Syndrome

The first message came via email. A scientist couple from the United States reported on their son David (name changed), who had just been diagnosed with FOXP1 syndrome—a mutation c.1240delC in the FOXP1 gene on the boy's chromosome 3p14.1. Chromosome 3p14.1 and chr3:g.71027087delG, these are positional data that human geneticists use to find their way around people's genetic makeup. A loss of a single base within the FOXP1 gene was apparently responsible for the boy's disease. This small change at this exact location in the genome turned out to be de novo, as it was not detected in either parent or a healthy sister. This information ended a long diagnostic odyssey during which the parents had tried to find out something about the causes of their child's illness. For the family, the diagnosis was a relief. It helped the parents to realize that they had done nothing wrong, and everything that had happened so far now found an explanation.

G. A. Rappold (✉)
Institute of Human Genetics, University of Heidelberg, Heidelberg, Germany
e-mail: Gudrun.Rappold@med.uni-heidelberg.de; https://www.klinikum.uni-heidelberg.de/personen/prof-dr-rer-natgudrun-rappold-3324

R. M. Holm-Hadulla et al. (eds.), *Intelligence - Theories and Applications*,
https://doi.org/10.1007/978-3-031-04198-3_6

The family was planning a trip to Europe and had read all the information they could find on Google and PubMed. They wanted to get more information about this autism syndrome with intellectual disability, which we had first described in 2010 (Horn et al., 2010; Hamdan et al., 2010). I invited the whole family and a staff member to my home. “This is David”—the front door had just opened when David rushed in without making eye contact, overtook his parents and sister, and disappeared into the nearest room to inspect it. His father apologized for this hasty arrival and inquired if it would be possible to look at all the rooms of the house from the basement to the roof with David, so that he could be assured that there was no one else hiding in the house who could be dangerous to him. This would help David a great deal to come to rest. And so it did. We were able to sit at a table and talk while drinking tea. For David, however, sitting still was only possible for a few minutes at a time. David—like many of the other children with FOXP1 syndrome—displayed several of the familiar autism symptoms: Fear of other people, inability to concentrate, inner restlessness and hyperactivity, and a limited ability to communicate and express himself due to his intellectual disability. Difficulties in establishing personal relationships and stereotyped movement patterns also often give the impression that autistic people live in a world all of their own.

“David has always been very different from his sister. That was noticeable from a very early age”; according to his mother. All attempts to make eye contact with her little son failed. The first developmental steps were also delayed. He began to speak very late, and then only single words. Doctors were also at a loss at first. Many specialists were consulted. An initial examination of the chromosomes yielded no result. Finally, a sequencing of the exome led to a definite result. Exome sequencing examines exactly the 1.5% of the genetic hereditary information in which the protein-coding regions are located. A deletion of a single base at position c.1240 of the FOXP1 gene led to a stop within the gene and to a chain break at position 414. A small error with a big effect. It had just become known that errors in the blueprint for the FOXP1 protein play a role in autism and intellectual disability. But what is its function in the healthy brain, which signaling pathways is it involved in, and what exactly is the damage caused by its absence? As we now know, an intact FOXP1 gene is necessary to ensure the right neural connections at the right time in brain development. At the time of diagnosis, David was already 4 years old. When David’s brain was tested, the score obtained was mild intellectual disability. His behavior was classified as autistic.

2 Autism Spectrum Disorder

Autism is a congenital disorder of perception and information processing in the brain, which can vary to a large extent. It is often accompanied by reduced, but rarely also by above-average intelligence. It is therefore also referred to as an autism spectrum disorder. This term has now become established, as it describes that a whole spectrum of phenotypes can be subsumed under this term. Low-functioning and high-functioning autism are other scientific terms. High-functioning autism is characterized by significantly delayed language development before the age of 3 and thus differs from Asperger syndrome, in which a language impairment is not present. Autism and Savant Syndrome with its insular gifts have been known to a wider cinema audience since the film "Rain Man": Dustin Hofmann in the lead role plays a person who not only lives in his own world but also possesses spectacular talents and can, for example, memorize an entire phone book after reading it only once. Greta Thunberg (Wikipedia, n.d.), the climate activist, has also talked openly about her Asperger's syndrome (https://www.watson.de/leben/gretathunberg). These above-averagely intelligent, often technically adept, but socially introverted people point out that high-functioning Asperger's syndrome can be both a gift and a deficit. However, it must be said that people with Asperger's syndrome make up only a small percentage among autistic people, and by far, the majority of people with autism spectrum disorder have an intellectual disability. Autism spectrum disorder is associated with intellectual disability, so this is rather the rule.

3 Intelligence Quotient, Giftedness, and Mental Retardation

People with a reduction in intelligence, whether or not associated with autistic traits, make up a large proportion of families seeking advice at a genetic outpatient clinic. In addition to genetic causes, which are increasingly being elucidated by sequencing the exomes or genomes of affected individuals, external factors such as teratogens or alcohol abuse during pregnancy can also lead to intellectual disability. Intelligence is measured by the intelligence quotient (IQ), which follows a normal distribution and whose midpoint is defined as 100. Approximately 3% of all people have an intellectual disability. Two to 3% of the population have an IQ that falls between 50 and 70, which is classified as mildly retarded. In Forrest Gump, an American literary adaptation starring Tom Hanks, mild mental retardation is inimitably illustrated with the lead character's wonderful line, "Life is like a box of chocolates; you never know what you are going to get." About 0.5–1% of the population, on the other hand, have a moderate (IQ 35–49) or severe (IQ 20–34) to profound (IQ below 20) reduction in intelligence, where completely different standards then apply.

There are many different genetic forms of intelligence impairment, which are often grouped into syndromes or otherwise classified. The most common syndromes associated with intellectual disability are Down syndrome (trisomy 21) and fragile X syndrome. In both cases, the genetic causes were already visible on chromosome level and therefore identified before other syndromes. Monogenetic forms of the disease, in which only one specific gene is affected, were elucidated much later. Several thousand different genes causing intellectual disability have become known over the past 30 years. There has been a dramatic increase in discoveries within the past decade due to next-generation sequencing (Rauch et al., 2012), and extreme genetic heterogeneity has been found as a result. This genetic heterogeneity of a supposedly similar disease phenotype came as a surprise. Human geneticists are therefore dealing with an extremely diverse group of genes and diseases affecting intelligence. These genes, which are mostly expressed in the cortical, striatal, and hippocampal neurons of the brain, have different functions in synaptic plasticity, transcriptional regulation, and chromatin remodeling. If one then further assumes that far more than half of all 20,000 human genes are expressed in the brain and also needed there, it is quite conceivable that malfunctions of any of these genes expressed in the brain could also lead to retardation. The end of the genetic clarification of the various forms of intelligence impairment is therefore still far from in sight, but all the frequent syndromes have been well described in the meantime.

Microdeletion and microduplication syndromes, in which there are several neighboring genes too many or too few, were technically easier to detect and therefore identified earlier in people with intellectual disability. It may sound strange, but both deletions and duplications of a particular chromosomal region can lead to a very similar phenotype in some cases. This is explained by the fact that for certain genes, chromosomal imbalances have particularly strong effects, when either too much or too little protein is present. The right balance, the right level of expression is needed for neuronal homeostasis.

It was also surprising to see how, in other cases, different mutations in the same gene can lead to completely different phenotypes. The phenotypic spectrum of a single gene turned out to be much broader than expected. Again, there is no universal mechanism or rule. As in all of animate nature, a wide range of possibilities also exist in genetics. Here, too, textbooks have to be adapted to the new findings and in some cases revised.

4 Higher Risk of Disease in Boys

Autism affects approximately 1–3% of children—boys four times more often than girls. In the case of Asperger's autism, only one in ten individuals is female (Baron-Cohen et al., 2005). But why is the male gender so much more prone to this disorder? Studies of human cells and the brains of mice have shown that the male sex hormone testosterone activates or inhibits certain "risk genes" in the brain in the period before and after birth (Stone et al., 2004). Thus, a sex-specific hormonal influence affecting only certain genes appears to underlie this unequal distribution between males and females. Since boys produce more testosterone than girls, variants in these genes are more likely to lead to autism spectrum disorder in them.

Among people with intellectual disabilities, boys are also much more often affected. One of the reasons is that X-linked intellectual disability accounts for approximately 10–20% of all cases. The first gene identified on the X chromosome in this context was the FMR gene, which leads to Fragile X syndrome. Fragile X syndrome is the most common intellectual disability of all, caused by the defect of a single gene. Only boys are severely affected here, because in girls the second X chromosome can compensate. Girls and women therefore have a clear advantage here.

5 Age Counts

The advanced age of couples who wish to have children plays a non-negligible role. Intellectual disability in a family is twice as high in couples aged 40 and over compared to younger couples. In families with a child suffering from trisomy 21, for example, the maternal age effect has been known for a long time, but fathers are also significantly involved in an increased risk due to an increased age. Indeed, much of the increased risk arises due to mutations during spermatogenesis (D'Onofrio et al., 2014). This age effect is also known to be present in autism spectrum disorders: Children of fathers over the age of 45 are approximately three times more likely to develop autism than children of fathers under the age of 25.

6 Gut and Head Brain Work Together

The brain and the gut with the two largest accumulations of neurons in the human body are closely connected via the spinal cord and the vagus nerve. Gene alterations in autism and intellectual disability may also be responsible for disorders of the gastrointestinal tract (Niesler & Rappold, 2021). Many of the genes associated with autism are active in both the brain and the digestive tract.

The 100 million nerve cells that surround our digestive tract are considered a kind of "second brain." This so-called gut brain communicates with the head brain and lets us make the right decisions triggered "from the belly." This "second brain," neuroscientists have found, is composed of some of the same cell types. Mental processes such as behavior and the digestive system with its "abdominal brain" Yes are probably far more closely coupled than previously thought (Rao & Gershon, 2016). Indeed, disorders of the gastrointestinal tract or digestive problems are more common than average in people with intellectual disability and autism spectrum disorder. However, these complaints have not yet been systematically recorded. Another difficulty is that, due to their usually limited communicative and intellectual abilities, people with intellectual disability and autism spectrum disorder find it difficult to communicate when, for example, digestive problems cause discomfort.

In FOXP1 syndrome, which is one of the more common autism disorders, it is already fairly well established that many of the affected individuals have swallowing difficulties and gastrointestinal problems (Fröhlich et al., 2019). With an adapted diet as well as drug treatment, the impaired esophageal and intestinal functionality observed in FOXP1 syndrome can now be addressed. Most importantly, it is now clear that the gastrointestinal problems are not primarily caused by the medications that sufferers have to take or their deviant eating habits—as was previously often assumed—but are due to the malfunction of the FOXP1 gene itself.

7 FOXP1 and Its Closely Related "Language Development Gene" FOXP2

The FOXP1 gene contains the blueprint of a protein that controls the switching on and off of many other genes to form neuronal connections in this way. Some of these, which are already needed early in brain development, are also regulated by FOXP1 in other areas, such as the enteric nervous system and muscle cells. In the striatum, the brain region that is significantly involved in language development, FOXP1 usually interacts with the FOXP2 protein to control other genes. They are therefore also called transcription factors. FOXP2 was identified as the first gene to cause a very specific language disorder through a mutation (Lai et al., 2001). For linguists, this represented a sensation: a mutation in a single gene passed down in a large family named KE. However, in the vast majority of families with a genetic language disorder, much more complex forms of inheritance exist. The KE family was therefore a stroke of luck in scientific research. However, the original hypothesis that FOXP2 might be the gene evolutionarily necessary for the formation of human speech, i.e., the fine motor skills in the larynx, could not be maintained in this exclusivity. It can be stated, however, that both genes, FOXP1 and FOXP2, have a role with language, whereby the effects of the malfunction of FOXP1 go beyond language and influences many other developmental processes in the brain and other tissues of the body.

8 Intelligence and Intellectual Disability: Two Sides of the Same Coin?

Twin studies have long suggested that genes play an important role in intelligence. "Nature or nurture" has been the big question, and related to that, what is the relationship between the two. A simple explanation is certainly not possible here, as it is more a matter of the dynamic mix of both influences. Research into intellectual disability also raises further questions: Can specific variants within a distinct gene cause intellectual disability, and other variants in the same gene possibly lead to higher performances? In other words: are intelligence and intellectual disability perhaps the result of subtle differences in the same hereditary traits, i.e., two sides of the same coin? That it is not that simple is shown by the data: Intelligence is a polygenic trait, likely involving hundreds or even thousands of gene variants (Goriounova & Mansvelder, 2019). An initial genetic DNA analysis of nearly 80,000 people and a comparison to their IQ scores initially crystallized 52 genes whose biology was associated with intelligence. However, their influence was small: together, they counted for only less than 5% in IQ scores. Further genome-wide association studies (GWAS) in an even larger number of people then identified many more variants in non-coding regions close to the genes that play a role in the regulatory processes of neurodevelopment. At least 1000 genes have thus been determined to be associated with intelligence (Savage et al., 2018).

This is in contrast to mental diseases in which a single mutation can trigger a disease. Thus, intelligence is assumed to be a polygenic, multifactorial trait, whereas many of the mutations that cause intellectual disability are monogenic in nature, i.e., they affect only one particular gene. Consequently, there is also no such thing as THE intelligence gene, but rather many gene variations distributed across the genome are involved in intelligence, which can only exert their effects under certain environmental conditions. Complicated ethical concerns about how this information could be used (keyword: designer babies with particularly high IQ) can therefore be relegated to the realm of fiction.

9 The Plasticity of the Brain

One of the greatest achievements of our brain is its adaptation to changing living conditions: brain plasticity. For example, scientists found in taxi drivers in London that there was an area of the brain in the grey matter of the posterior hippocampus that was particularly developed due to their spatial memory owing to their navigation through the many streets of the city (Maguire et al., 2011). A Swedish study found that when learning a new language, the very brain areas responsible for language development develop.

Continuous training and a stimulating, supportive environment therefore supports memory processes and lead to learning successes and even change the architecture of the brain. Learning successes are also possible for people with intellectual disabilities and autism if this is started early. This is why early diagnostic detection and subsequent support programs for individuals with disabilities are so important.

10 Animal Models as Important Intermediate Steps to Understanding

Animal models can be used to understand the deficits that result from the absence of a particular gene in the developing brain. Animal models are also helpful to test novel therapeutic options. Let us return to the FOXP1 syndrome: the protein version of the mouse and that of humans are very similar. Mice with a complete loss of the FOXP1 gene in the nervous system are initially born with a largely normally developed brain. During the first week of life, the striatum of the brain, which is important for perception and behavior, changes (Bacon et al., 2015). Changes also occur in a centrally located brain structure, the hippocampus, indispensable for the formation of long-term memory and recall, which have implications for signal processing. In the affected neurons, the branching of the neurites and the so-called excitation conduction, through which signals are passed between neurons, changes (Bacon et al., 2015). In addition to the degenerated striatum, adjacent brain structures, the ventricles, are enlarged in these mice. Enlarged ventricles could also be detected in humans with a FOXP1 mutation. These changes trigger behavioral abnormalities in mice that are comparable to the symptoms in autistic patients: The mice hardly take any notice of their conspecifics and do not make contact. In addition, stereotypical, repetitive behaviors, reduced learning ability, and hyperactivity are noted. The FOXP1 mice's ultrasonic vocalization (mice communicate via sounds in the ultrasonic range) was also found to be impaired and showed parallels to the disorders in patients with FOXP1 mutation (Fröhlich et al., 2017). Thus, important insights into behavior and neural networks emerge. Based on these observed similarities between human and mice, therapeutic approaches can now be tested out before considering clinical trials with patients.

11 Life Perspectives

Children with intellectual disabilities and/or autism spectrum disorder dominate a family's daily life, and usually by day and night. Restless sleep at night can be just one of the many stresses on a family. These children are usually particularly sensitive to sensory stimuli, while the sense of pain may be reduced. Both phenomena are not easy to bear. However, many children with an intellectual disability, especially those with a mild and moderate impairment, can also learn many things, they just need more time for this and more effort is required for them than for other children. Here the strategy of small steps, short learning units, visual learning, music, and sports are of particular importance. Therefore, confirmed diagnoses can also indicate in which areas therapeutic support is particularly useful. With the diagnoses, supportive measures and help can be offered to the families. Knowing the cause of an illness also makes it easier to deal with very practical matters, such as negotiations with health insurance companies. Last but not least, families with a similar fate can give each other important practical and emotional support in self-help groups.

Children are very lucky if their parents are committed to their needs for support and find the right schools or workshops for disabled people. David is lucky to have a home that does everything humanly possible to support him. He goes to a special school for children with learning disabilities and, according to his parents, has already made great progress there. But he will probably never be able to lead a normal, self-determined life. Even now he only speaks half sentences and is difficult to understand for outsiders. However, he has a relatively good memory, is lovable and, like the other children with FOXP1 syndrome, is making great efforts to overcome his limitations. In any case, he has already clearly set his professional goal: to become a fire truck driver.

References

Bacon, C., Schneider, M., Le Magueresse, C., Froehlich, H., Sticht, C., Gluch, C., Tucker, P., Monyer, H., & Rappold, G. (2015). Brain-specific Foxp1 deletion impairs neuronal development and causes autistic-like behaviour. *Molecular Psychiatry, 20*(5), 632–639.

Baron-Cohen, S., Knickmeyer, R. C., & Belmonte, M. K. (2005). Sex differences in the brain: Implications for explaining autism. *Science, 310*(5749), 819–823.

D'Onofrio, B. M., Rickert, M. E., Frans, E., Kuja-Halkola, R., Almqvist, C., Sjölander, A., Larsson, H., & Lichtenstein, P. (2014). Paternal age at childbearing and offspring psychiatric and academic morbidity. *JAMA Psychiatry, 71*(4), 432–438.

Fröhlich, H., Rafiullah, R., Schmitt, N., Abele, S., & Rappold, G. A. (2017). Foxp1 expression is essential for sex-specific murine neonatal ultrasonic vocalization. *Human Molecular Genetics, 26*(8), 1511–1521.

Fröhlich, H., Kollmeyer, M. L., Linz, V. C., Stuhlinger, M., Groneberg, D., Reigl, A., Zizer, E., Friebe, A., Niesler, B., & Rappold, G. A. (2019). Gastrointestinal dysfunction in autism displayed by altered motility and achalasia in Foxp1+/- mice. *PNAS, 116*(44), 22237–22245.

Goriounova, N. A., & Mansvelder, H. D. (2019). Genes, Cells and Brain Areas of Intelligence. *Frontiers in Human Neuroscience, 13*, 44.

Hamdan, F. F., Daoud, H., Rochefort, D., Piton, A., Gauthier, J., Langlois, M., Foomani, G., Dobrzeniecka, S., Krebs, M. O., Joober, R., Lafrenière, R. G., Lacaille, J. C., Mottron, L., Drapeau, P., Beauchamp, M. H., Phillips, M. S., Fombonne, E., Rouleau, G. A., & Michaud, J. L. (2010). De novo mutations in FOXP1 in cases with intellectual disability, autism, and language impairment. *American Journal of Human Genetics, 87*(5), 671–678.

Horn, D., Kapeller, J., Rivera-Brugués, N. R., Moog, U., Lorenz-Depiereux, B., Eck, S., Hempel, M., Wagenstaller, J., Gawthorpe, A., Monaco, A. P., Bonin, M., Riess, O., Wohlleber, E., Illig, T., Bezzina, C. R., Franke, A., Spranger, S., VillavicencioLorini, P., Seifert, W., … Strom, T. A. (2010). Identification of FOXP1 deletions in three unrelated patients with mental retardation and significant speech and language deficits. *Human Mutation, 31*(11), E1851–E1860.

Lai, C. S., Fisher, S. E., Hurst, J. A., Vargha-Khadem, F., & Monaco, A. P. (2001). A forkhead-domain gene is mutated in a severe speech and language disorder. *Nature, 413*(6855), 519–523.

Maguire, E. A., Gadian, D. G., Johnsrude, I. S., Good, C. D., Ashburne, J., Frackowiak, R. S. J., & Frith, C. (2011). Navigation-related structural change in the hippocampi of taxi drivers. *Proceedings of the National Academy of Sciences of the United States of America, 297*(8), 4398–4403.

Niesler, B., & Rappold, G. A. (2021). Emerging evidence for gene mutations driving both brain and gut dysfunction in autism spectrum disorder. *Molecular Psychiatry, 26*, 1442. https://doi.org/10.1038/s41380020-0778-5

Rao, M., & Gershon, M. D. (2016). The bowel and beyond: The enteric nervous system in neurological disorders. *Nature Reviews. Gastroenterology & Hepatology, 13*(9), 517–528.

Rauch, A., Wieczorek, D., Graf, E., Wieland, T., Endele, S., Schwarzmayr, T., Albrecht, B., Bartholdi, D., Beygo, J., Di Donato, N., Dufke, A., Hempel, M., Horn, D., Hoyer, J., Joset, T., Röpke, A., Moog, U., Riess, A., Thiel, C. T., … Strom, T. M. (2012). Range of genetic mutations associated with severe non-syndromic sporadic intellectual disability: An exome sequencing study. *Lancet, 380*(9854), 1674–1682.

Savage, J. E., Jansen, P. R., Stringer, S., Watanabe, K., Bryois, J., de Leeuw, C. A., Nagel, M., et al. (2018). Genome-wide association meta-analysis in 269,867 individuals identifies new genetic and functional links to intelligence. *Nature Genetics, 50*(7), 912–919.

Stone, J. L., Merriman, B., Cantor, R. M., Yonan, A. L., Conrad Gilliam, T., Geschwind, D. H., & Nelson, S. F. (2004). Evidence for sex-specific risk alleles in autism spectrum disorder. *American Journal of Human Genetics, 75*(6), 1117–1123.

Wikipedia. (n.d.). *Greta-Thunberg and Asperger's syndrome*. Retrieved from https://de.wikipedia.org/wiki/Greta_Thunberg, https://www.watson.de/leben/gretathunberg/846867677

Gudrun A. Rappold is Full Professor of Human Genetics at the University of Heidelberg, where she has headed the Department of Molecular Human Genetics from 2003 to 2021. After studying biology, chemistry, and physics at Stanford University, Heidelberg, and Konstanz, she worked as a research associate at the MRC Mammalian Genome Unit in Edinburgh, Scotland; European Molecular Biology Lab (EMBL), Heidelberg, and Imperial Cancer Research Fund in London, England. Her work focuses on the molecular basis of genetic diseases, particularly neurodevelopmental disorders and endocrinological diseases, using animal models, iPSCs and genome editing, among other tools. She and her research group have identified over 30 novel genes underlying developmental disorders. She is a reviewer and scientific advisor to national and international organizations and courts, a patent holder and consultant to the biomedical industry, and serves on foundations and as an editorial board member of scientific journals. She is the author of more than 300 original papers, reviews and book chapters and one book in the field of genetics, and the recipient of several awards. She has been involved in interdisciplinary initiatives, including as a Fellow at the Marsilius-Kolleg and with colleagues in Freiburg on genetic minority studies. Since 2022, she is active as a Senior professor.

Part II
Psychology of Intelligence

Chapter 7
Intelligence: The Psychological View

Joachim Funke

Abstract This chapter presents a small sample of psychological research on the topic of "human intelligence." Intelligence is a central construct in modern psychology for describing differences in cognitive performance. Somewhat broader conceptualizations view human adaptation to the environment and shaping the environment to our advantage as central to intelligent action. A brief overview of different conceptions of intelligence is given. The "dark side" of intelligence (the destructive potential) is also addressed. The peculiarities of human intelligence compared to artificial intelligence are emphasized.

1 Introduction

Intelligence is a predicate with which one likes to adorn oneself (or even more popular: with which one is adorned by others). Nobody wants to be called "stupid" or "foolish," the stupidity of others can be made fun of.

While the measurement of physical strength in the form of the "Olympic games" was already known in ancient times, there were also intelligence-demanding tasks such as the riddle of the Sphinx, who, according to Greek mythology, besieged Thebes and would not let anyone pass their way who did not correctly answer her question: "What is four-footed in the morning, two-footed at noon, three-footed in the evening?" Only the clever Oedipus knew the answer (correct answer: man), whereupon the Sphinx committed suicide, thus saving Thebes. But "Olympiads of

The text is based on a talk given as the opening lecture at the 145th Annual Conference of the Evangelical Research Academy on Jan. 8, 2021, at Berlin, and published in their 2021 conference proceedings under the title "Was ist Intelligenz? Die psychologische Sicht".

J. Funke (✉)
Department of Psychology, University of Heidelberg, Heidelberg, Germany
e-mail: Joachim.funke@psychologie.uni-heidelberg.de

R. M. Holm-Hadulla et al. (eds.), *Intelligence - Theories and Applications*,
https://doi.org/10.1007/978-3-031-04198-3_7

the mind" (comparable to the Olympic Games) were not developed at that time, except for the "symposia" (guest paintings) as preforms of scientific conferences.

2 Working Definition

In a good scientific paper, it is appropriate to clearly define the central construct—in our case: "intelligence." Now, this is extraordinarily difficult because of the high level of abstraction of the processes that are to be discussed here. Some, such as the historian Edwin Boring (1923), therefore prefer to refer to the measurement procedure ("operational definition" sensu Bridgman, 1927) for the sake of simplicity: "Intelligence is what the intelligence test measures." As correct as this statement is, it leaves us in the dark about what is to be measured.

A working definition accepted by 52 prominent intelligence researchers in 1994, on the occasion of a survey of 131 leading intelligence researchers,[1] is as follows:

> A very general mental capability that, among other things, involves the ability to reason, plan, solve problems, think abstractly, comprehend complex ideas, learn quickly and learn from experience. It is not merely book learning, a narrow academic skill, or test-taking smarts. Rather, it reflects a broader and deeper capability for comprehending our surroundings—"catching on", "making sense" of things, or "figuring out" what to do.

There is a lot of content in there: thinking, planning, problem-solving, learning, understanding. Basically, the concept comprises everything that modern cognitive research calls "higher" cognitive processes in humans (in contrast to the "simple" process of perception, for example).

3 Theoretical Issues

The beginning of the twentieth century saw the emergence of the first theories of intelligence that we now regard as classics. Five important personalities will be briefly introduced below who are still considered influential shapers of our modern theories of intelligence. These five individuals are (1) Alfred Binet (global intelligence and its diagnostics), (2) Lewis Terman (IQ and the Stanford–Binet test), (3) Charles Spearman (the two-factor theory), (4) Louis L. Thurstone (the theory of "primary mental abilities"), and (5) David Wechsler (a pragmatic compromise).

Alfred *Binet* (1857–1911), on behalf of the French Ministry of Education, together with Theodore Simon, reported in 1905 on the development of the first "intelligence test" to detect mentally handicapped children in school classes in Paris. Their measuring procedure consisted of 30 different tests; these were revised in 1908 and further developed as the Stanford–Binet test in the USA as early as

[1] "Mainstream science on intelligence", *December* 13, 1994. Wall Street Journal, p. A18.

1916 by Lewis Terman (see below). The term IQ was also mentioned for the first time at this time. The intelligence quotient (IQ) according to William Stern (1912) is defined as the ratio of "age of intelligence" (AI; i.e., the level of intelligence of an individual in relation to the mental capacity of the age-appropriate intelligence average) to "age of life" (AL) multiplied by 100 (IQ = AI/AL*100).

With his test development, Alfred Binet initiated decisive progress in intelligence diagnostics and set standards that are still valid today (see also Funke, 2006). These include in particular the increase in reliability (= increase in measurement accuracy) on six different grounds: (1) through multi-item measurement, (2) through a systematic gradation of difficulty, (3) through the standardization of test instruction, test administration, and test evaluation, (4) through test normalization by comparison with different age groups, (5) through a pronounced behavioral orientation in which the performance achieved counts, not the subjective assessment of performance, and last but not least (6) through the conviction that the test result must not be the sole basis of a person's assessment.

Lewis *Terman* (1877–1959) introduced the Binet–Simon intelligence test in the USA. In the light of the requirements of the First World War (selection of intelligent military personnel to operate the then still very error-prone military technology), he further developed the original test into the so-called "Army Alpha" test, which was used on a mass scale for the first time and thus ushered in an enormous upswing in intelligence diagnostics.

Terman also launched the first longitudinal study of gifted students (the "Stanford Genius Project"; participants were called "termites"): In 1921, a total of 1528 gifted 12-year-olds with an IQ greater than 140 were recorded for the first time, then again and again tested (in the years 1928, 1936, 1940, 1945, 1950, 1955, and 1960). In 2003, 200 of the original 1909 cohort were still alive. More than half of the gifted students graduated from college (normal at the time for only 8% of a cohort), yet looking back over 25 years of longitudinal testing, Terman drew what he considered a sobering conclusion: "At any rate, we have seen that intellect and achievement are far from perfectly correlated" (Terman & Oden, 1947, p. 352).

Charles *Spearman* (1863–1945) presented a "two-factor theory" of intelligence as early as 1904: In addition to a general factor *g*,[2] which is involved everywhere, specific factors *s* (e.g., numeracy or linguistic ability) are still involved in a test task. The basis of his theory was the then-novel method of correlation calculus, later factor analysis. The complementary nature of *g* and *s* was important to him: *g* cannot be trained, whereas *s* can; *g* represents "noegenetic processes" (= understanding processes) in contrast to sensory and motor processes.

Louis L. *Thurstone* (1887–1955) presented an intelligence model based on several common factors ("primary mental abilities", PMA) in his 1938 book. He considered *g* to be a statistical artifact. Intelligent behavior, for him, results from the interaction of several independent factors (the seven "primary abilities"): (1) verbal

[2] The abbreviation *g* (for ""general intelligence") has become accepted as an acronym. Malicious tongues claim that *g is to* psychology what *C* (carbon) is to chemistry (Ree & Earles, 1993).

comprehension, (2) verbal fluency, (3) reasoning, (4) spatial imagination, (5) retention, memory, (6) numeracy, numerical reasoning, (7) perceptual speed, attention.

David *Wechsler* (1896–1981) introduced IQ as a deviance quotient in 1932 because in adults the classic IQ as a ratio of age of intelligence to the age of life (IQ = IA/LA*100) is not useful owing to the ever-increasing age (for the same performance, IQ decreases with increasing age). The "deviance ratio" introduces the reference to a normal distribution of the corresponding age group, with a mean of 100 and a standard deviation of 15. The comprehensive test battery developed by Wechsler distinguishes between a verbal IQ and an action IQ; the test battery is constantly revised and is still in use today under the names "Wechsler Adult Intelligence Scales - Revision IV" (WAIS-IV) and "Wechsler Intelligence Test for Children" (WISC).

Modern theories of intelligence have also been formulated numerous times—and there are good overviews of them, so I will refer to them here rather than rehashing these theories (see, e.g., Sternberg, 2018; Sternberg & Kaufman, 2011; Wilhelm & Schroeders, 2019).

However, I would like to mention one approach that has gained some currency: Howard *Gardner* (1993) has attracted attention with his assumption of multiple (initially seven, now nine) independent "intelligences": (1) linguistic–linguistic intelligence: e.g., language comprehension, writing, speaking, and reading; (2) logical–mathematical intelligence, e.g., mental arithmetic; (3) pictorial–spatial intelligence: e.g., reading a map, stowing suitcases; (4) musical intelligence: e.g., playing an instrument, composing a piece; (5) motor intelligence: e.g., control of body movements, dance, and sports; (6) intrapersonal intelligence: the ability to deal with oneself (intrapersonal); (7) interpersonal intelligence: the ability to deal with other people ("social intelligence"); (8) naturalistic intelligence in the sense of a special relation to nature; (9) spiritual, "existential" intelligence in the sense of wisdom and transcendence. Figure 7.1 illustrates these different "intelligences" and also names prominent representatives of each type.

Gardner gives an extensive list of criteria as reasons for the assumption of independent "intelligences": potential isolation of a special brain structure, e.g., due to brain damage; the existence of extraordinary talents; identifiable core function of human beings; characteristic individual history; evolutionary plausibility; support by data from experimental psychology; support by data from psychometry; suitable for coding in a symbol system (e.g., the symbol systems of musical notes, letters, numbers). This list rules out, for example, "chess intelligence", since it lacks, for example, evolutionary plausibility.

The most widely used conceptualization today is the theory developed by Cattell, Horn, and Carroll (called the "CHC model"; see McGrew, 2005; Schneider & McGrew, 2012). According to this model, a three-layered schema with a single general cognitive ability ("*g*") on the third (top) layer ("stratum" called), eight abilities on the second stratum, and about 66 abilities on the first (lowest) stratum are to be assumed (Carroll, 1993). Second stratum abilities included fluid (Gf) and crystalline intelligence (Gc), memory, visualization, and several other traits. First stratum abilities within the category of fluid abilities Gf included inductive, sequential

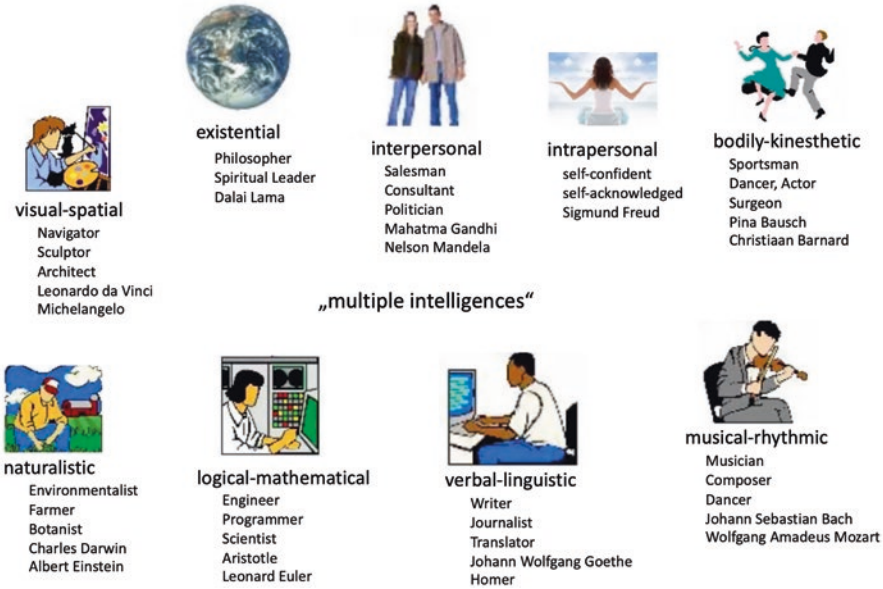

Fig. 7.1 Illustration of multiple intelligences according to Howard Gardner. (Source: https://openmind-akademie.de/hochbegabung/theorie-der-multiplen-intelligenz/)

(deductive), quantitative, and Piagetian reasoning. Other factors of the second stratum were similarly divided into narrower primary factors. Figure 7.2 shows the development of the various theories of intelligence and their culmination in the combined CHC model of Cattell (1963), Horn (1976), and Carroll (1993).

In the second stratum, for example, three of the eight factors are speed factors. These include a processing speed factor measured by reaction time tasks and other timed tasks (e.g., finding synonym for common words). A separate broad cognitive speed factor is measured by tests of numerical ability (e.g., single-digit addition tasks) and perceptual speed (e.g., letter–picture matching), as well as general test speed factors (e.g., the number of items checked within a time limit). The third factor of the second stratum is a broad factor of memory, which is measured primarily by fluency ("fluidity") tests. Examples of fluency tests are those in which a subject has, for example, 2 min to "list all the 4-letter words you can think of that begin with B and end with T" or "write down as many synonyms as you can for the word 'good.'" The "broad" skills on stratum 2 are named in detail as follows in the synopsis: Gc—crystallized intelligence, Gf—fluid intelligence, Gs—processing speed, Gt—reacting or decision-making speed, Gsm—short-term or immediate memory, Glr—long-term memory storage and retrieval, Grw—reading and writing ability, Gq—quantitative reasoning, Gv—visual processing, and Ga—auditory processing.

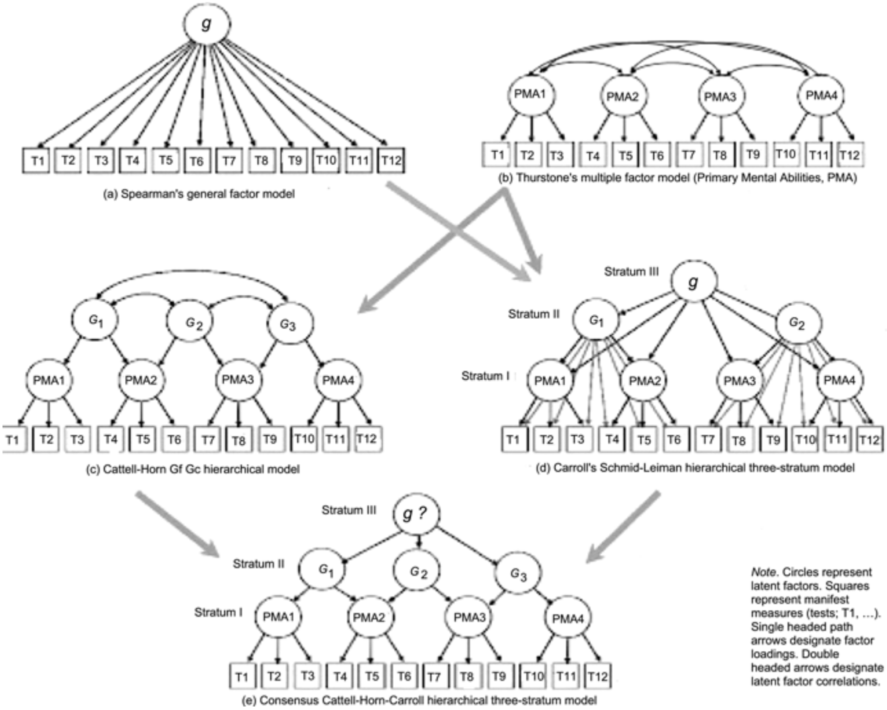

Fig. 7.2 The development of the CHC model with its three layers (**e**), derived from Spearman's general factor model (**a**), Thurstone's notion of "primary mental abilities" (PMA; **b**), the Cattell-Horn assumption of fluid and crystalline intelligence (**c**), and the hierarchical three-layer model (**d**), with circles as latent and quadrilaterals as manifest variables (tests T1 … T*n*. Source: Institute for Applied Psychometrics IAP, Dr. Kevin McGrew, 4-11-2014)

4 Measurement Issues and Critical Points

The intelligence test is probably one of the most successful products on the market of saleable psychic goods. Whole industries (test publishers such as, e.g., the internationally operating companies "Educational Testing Service," "Hogrefe Publishing," "Pearson Assessments," or "Schuhfried") live from it. Notwithstanding this, the question may be asked whether (and if so, how) mental characteristics such as the construct of "intelligence" can be measured, analogously to a measurement of force in physics (critically: Gould, 1996).

The fact that this type of diagnostics has been continuously perfected for over 100 years and that the IQ test is, therefore, the longest-optimized measurement instrument in psychology is both a blessing and a curse: it is a blessing because measurement precision has reached an enormously high level of quality; it is a curse because, although we have gradually optimized the selected set of tasks for over 100 years, we have failed to "retread" the measurement approach fundamentally. This leads to the criticism of the present measurement methods.

Criticism of the existing measurement methods is based on the following points: (a) they often consist of puzzle questions; (b) all relevant information is available on a silver platter; (c) there is only one correct solution; (d) the tasks do not have a time dimension, there is no need to deal with the consequences of decisions; (e) mainly analytical intelligence is measured—the measurement of social and emotional abilities, which are subsumed under the keyword "social" and "emotional" intelligence, is missing.

In other words: Intelligence tests are "altogether too little complex"—as the German writer Hans-Magnus Enzensberger (2007) succinctly and compactly puts it in an essay worth reading with the beautiful title "Im Irrgarten der Intelligenz. Ein Idiotenführer" (in English: "In the maze of intelligence. An idiot's guide"; similar: Sternberg, 2016).

Another line of criticism should be mentioned here, which has recently been vividly advocated by Robert Sternberg: "The Dark Side of Intelligence" or the *self-destruction hypothesis*. Sternberg (2019, p. 8) sees the dark side of intelligence there, "… if a person's creative, analytical, or practical skills are used for dark ends." He advocates the self-destruction hypothesis: people who are considered "intelligent" according to current test standards (i.e., actually: "smart people") are ruining humanity. For this reason, he considers "adaptive" intelligence (in the sense of collective efforts) to be more important than "general" intelligence (in the sense of individual—egoistic—survival; see Sternberg, 2021).

The concept of intelligence is very close to the concept of wisdom, a concept that is *not* addressed in conventional IQ tests. Wisdom characteristics that would need to be taken into account include life experience, diversity of perspective, self-reflection, knowledge of how to live a "good" life, and knowledge of the fundamental pragmatics of human life (see, e.g., Baltes & Smith, 2008; Fischer, 2015; Glück, 2019). To adequately capture these characteristics, completely different measurement approaches would be needed than have been practiced to date.

Another possible alternative for the assessment of intelligent action (and thus a possible alternative to the IQ test) is the measurement of performance and behavior in goal-directed action in computer-simulated scenarios. This idea arose as a reaction to the discomfort with IQ tests that has been noticeable since the 1970s (not close enough to reality, hardly valid in everyday life). At the suggestion of Dietrich Dörner (Bamberg, Germany), computer-simulated scenarios ("micro-worlds") were used. The aim was to record "complex problem solving", i.e., to study how humans deal with uncertainty in complex situations (Dörner, 1981).

This plan was favored by the availability of mainframe computers, first in computer centers and later (as small desk-top computers) in psychological laboratories. This made it possible to create controlled requirements in the form of simulation models in which test subjects had to prove themselves as actors (managers, mayors, developmental aid workers). One of the open questions put by Putz-Osterloh (1981) was: What is the relationship between measured test intelligence and solving complex problems? The answer of the Dörner group (see, e.g., Dörner et al., 1983) was clear: none! Of course, there was opposition to this position (e.g., Funke, 1983; Hörmann & Thomas, 1989; Kretzschmar et al., 2016). The dispute between the two sides is characterized by two different perspectives: While intelligence research tends to argue in terms of cognitive structures, research on complex problem solving is more process-oriented. The current position can be found in a summary paper by Dörner and Funke (2017).

Five characteristics of a complex problem show their closeness to more everyday-life requirements, different from what is captured in the intelligence test. These five characteristics are (1) *complexity* (= a system to be understood consists of too many different variables; as a consequence, the processing capacity of the problem solver is exceeded, and therefore there is a need for information reduction); (2) *interconnectedness* (= the variables involved are strongly interconnected; as a consequence, the problem solver must take into account the (mutual) dependencies between the variables involved; hence, there is a need for model building and information structuring); (3) *dynamics* (= the system in question continues to develop even without the actor's intervention; as a consequence, there is only limited time available for reflection, and hence there is a need for rapid decisions due to superficial information processing); (4) *intransparency* (= the information that the actor needs for their decisions is not fully accessible, partly for reasons of principle, partly for reasons of time; as a consequence, there is a need for active information gathering); (5) *polytely* (= multi-objective; i.e., not only one criterion has to be optimized, but many, occasionally contradictory conditions have to be taken into account; as a consequence, the problem solver has to build up a differentiated goal structure with rules for conflict resolution and there is a need for multidimensional information evaluation).

This conception of complex problems was the basis of the assessment of problem-solving competencies within the international PISA study in 2012 (OECD, 2014), which aimed to capture the problem-solving potential of 15-year-old students from 67 nations (see in detail Ramalingam et al., 2017; for PISA results for Canada and the USA, see Dossey & Funke, 2016). Since it was politically undesirable to speak of "intelligence" in this context (the concept sounds so immutable), it was politically preferred to speak of (trainable) cognitive "competencies" (Funke et al., 2018).

In dealing with complex problems posed in computer-simulated scenarios, the three types of intelligence necessary for life success (in the sense of "success intelligence") according to Sternberg (1996) come to the fore: (a) creative intelligence, to detect the really important problems; (b) analytical intelligence, to solve these problems; and (c) practical intelligence, to apply the problem solutions found and to enforce them in the social context.

5 Artificial and Human Intelligence

One aspect that the public is following with great excitement concerns the (supposed) race between natural (human) and artificial (machine) intelligence. The question is: When will AI and its superintelligence take over the world? In his book "The singularity is near" (2005), the American author Ray Kurzweil (head of the technology department at Google since 2012) described this point as the "technological singularity," as the turning point in history from which humanity can achieve immortality.

What are the strengths of artificial systems? Machine systems score high on special (well-defined) requirements (such as chess or Go—but not on the Middle East problem); on pattern recognition (such as recognition of signatures—but not on recognizing black melanoma on dark skin); they shine with high speed and fast learning (learning by processing large amounts of data, not by insight).

In comparison, what are the unsurpassed strengths of humans? Dealing with uncertainty and with novelty. Imagination and play. Wit and irony. Spirituality. Laughter: Interestingly, artificial systems do not laugh. Humans, unlike machines, possess the characteristic of mortality and the principal capacity for reproduction or even suicide—I know of no machine system that unplugs itself. Culture and history also make up the human being, both individually in the personal life story and overarchingly (for the species) in human history.

Finally, concerning the issues revolving around the concepts of "consciousness, freedom, free will," one could crudely say: *humans act based on intention, machines execute based on instruction*. That is one of the reasons why I think it is wrong to say that AI systems (such as the software for self-driving cars) are equipped with so-called "ethics" (e.g., with the rule to rather run over old people than small children in case of emergency). Such a rule is not ethics yet, of course—it's just preprogrammed decision rules that self-driving cars need. But a set of rules does not make ethics.[3]

That machine learning techniques have long since led to products that supposedly "intelligently" assess a person's creditworthiness or their "risk of recidivism" for criminal offenses only highlights one of our society's problems in evading decisions for which humans should take responsibility. There have long been calls to stop accepting this kind of "black box" AI (Rudin, 2019).

As a little amusement on the power of AI to generate texts, here is an illustrative example: I gave the text-generating AI algorithm "GPT-2" (available online at https://transformer.huggingface.co) the first sentence of this article (see above: "Intelligence is a predicate with which one likes to adorn oneself (or even better: with which one is adorned by others)") as input and asked the software to continue the beginning of the text. Thereupon the following suggestion came as an output of the AI system for a second sentence: "Intelligence is the ability to recognize the fact that someone is acting in a certain way, in particular, when such actions result in consequences that are unpredictable". Sounds like a real sentence, but is of course nonsense. Not a threat to authors, but it is to editors of scientific journals: The first computer-generated "scientific" texts have already been printed in conference proceedings and recently had to be retracted.[4]

[3] Ethics often show themselves only in the breaking of rules, e.g., in the murder of tyrants.

[4] See https://retractionwatch.com/2021/02/17/publisher-retracting-five-papers-because-of-clearevidence-that-they-were-computer-generated/. Retrieved 10.08.2021.

Incidentally, the human side of intelligence also includes *folly* (which is not to be equated with stupidity) as its shadow side. Barbara Tuchman (1984) writes in her book "The march of folly" about the folly of those in power and makes it clear that in the field of politics a lot of wrong decisions can be found that have cost many human lives. This is not a new insight—Plato writes in his "Politeia": "And so the state will be administered to us and to you watchfully and not dreamingly, as now most are administered by those who engage in shadowy skirmishes with each other and divide over the supreme power, as if it were an even great good" (Politeia, 521d). Dörner (2021) describes the follies of political decision-makers, which he sees primarily in (1) simplifications of reality (complexity reduction), (2) demonstrations of competence, and (3) securing group coherence ("groupthink"; see also Janis, 1982). In doing so, he ties in with his earlier observations on the "logic of failure" (Dörner, 1996).

6 Concluding Remarks

The construct of intelligence fulfills an important selection function in our modern meritocracy. That is why we will not be able to let go of it any time soon. However, we can ensure that the hitherto narrow understanding of intelligence as an indicator of primarily analytical (and egoistic) ability is replaced by a broader understanding that focuses on the adaptive advantage of our species as a whole ("adaptive intelligence" in the sense of Sternberg, 2021). The previously good predictive power of *g* with regard to the expression of other psychological variables does not have to be lost in the process (see Stern & Neubauer, 2016).

Acknowledgment I sincerely thank Dr. Marlene Endepohls (Heidelberg) for her comments and remarks.

References

Baltes, P. B., & Smith, J. (2008). The fascination of wisdom: Its nature, ontogeny, and function. *Perspectives on Psychological Science, 3*(1), 56–64. https://doi.org/10.1111/j.1745-6916.2008.00062.x

Binet, A., & Simon, T. (1905). Méthodes nouvelles pour le diagnostic du niveau intellectuel des anormaux. *L'Année Psychologique, 11*, 191–244.

Boring, E. G. (1923). Intelligence as the tests test it. *New Republic, 36*, 35–37.

Bridgman, P. W. (1927). *The logic of modern physics*. Macmillan.

Carroll, J. B. (1993). *Human cognitive abilities: A survey of factor-analytic studies*. Cambridge University Press.

Cattell, R. B. (1963). Theory of fluid and crystallized intelligence: A critical experiment. *Journal of Educational Psychology, 54*, 1–22. https://doi.org/10.1037/h0046743

Dossey, J. A., & Funke, J. (2016). Canadian and United States students' performances on the OECD's PISA 2012 problem-solving assessment. *Canadian Journal of Science, Mathematics and Technology Education, 16*(1), 92–108. https://doi.org/10.1080/14926156.2015.1119332

Dörner, D. (1981). Über die Schwierigkeiten menschlichen Umgangs mit Komplexität [On the difficulties of humans coping with complexity]. *Psychologische Rundschau, 32*, 163–179.

Dörner, D. (1996). *The logic of failure. Recognizing and avoiding error in complex situations*. Basic Books.

Dörner, D. (2021). *Torheit in der Politik* [*Folly in politics]*. University of Bamberg (unpublished manuscript).

Dörner, D., & Funke, J. (2017). Complex problem solving: What it is and what it is not. *Frontiers in Psychology, 8*(1153), 1–11. https://doi.org/10.3389/fpsyg.2017.01153

Dörner, D., Kreuzig, H. W., Reither, F., & Stäudel, T. (1983). *Lohhausen. Vom Umgang mit Unbestimmtheit und Komplexität [Lohhausen. On dealing with uncertainty and complexity]*. Huber.

Enzensberger, H. M. (2007). *Im Irrgarten der Intelligenz. Ein IdiotenfÜhrer [In the maze of intelligence. An idiot's guide]*. Suhrkamp.

Fischer, A. (2015). Wisdom - The answer to all the questions really worth asking. *International Journal of Humanities and Social Science, 5*(9), 73–83.

Funke, J. (1983). Einige Bemerkungen zu Problemen der Problemlöseforschung oder: Ist Testintelligenz doch ein Prädiktor? [Some remarks on problems in problem-solving research or: Is test intelligence a predictor after all?]. *Diagnostica, 29*, 283–302.

Funke, J. (2006). Alfred Binet (1857 bis 1911) und der erste Intelligenztest der Welt [Alfred Binet (1857 to 1911) and the world's first intelligence test]. In G. Lamberti (Ed.), *Intelligenz auf dem PrÜfstand—100 Jahre Psychometrie [Intelligence on the test bench-100 years of psychometrics]* (pp. 23–40). Vandenhoeck & Ruprecht.

Funke, J., Fischer, A., & Holt, D. V. (2018). Competencies for complexity: Problem solving in the twenty-first century. In E. Care, P. Griffin, & M. Wilson (Eds.), *Assessment and teaching of 21st century skills. Research and applications* (pp. 41–53). Springer. https://doi.org/10.1007/978-3-319-65368-6_3

Gardner, H. (1993). *Multiple intelligences: The theory in practice*. Basic Books.

Glück, J. (2019). Wisdom. In R. J. Sternberg & J. Funke (Eds.), *The psychology of human thought: An introduction* (pp. 307–326). Heidelberg University Publishing. https://books.ub.uni--heidelberg.de/index.php/heiup/catalog/book/470

Gould, S. J. (1996). *The mismeasure of man (revised and expanded)*. W. W. Norton.

Hörmann, H.-J., & Thomas, M. (1989). Zum Zusammenhang zwischen Intelligenz und komplexem Problemlösen [On the relationship between intelligence and complex problem solving]. *Sprache & Kognition, 8*, 23–31.

Horn, J. L. (1976). Human abilities: A review of research and theory in the early 1970s. *Annual Review of Psychology, 27*(1), 437–485. https://doi.org/10.1146/annurev.ps.27.020176.002253

Janis, I. L. (1982). *Groupthink. Psychological studies of policy decisions and fiascoes* (Revised and enlarged ed.). Houghton Mifflin.

Kretzschmar, A., Neubert, J. C., Wüstenberg, S., & Greiff, S. (2016). Construct validity of complex problem solving: A comprehensive view on different facets of intelligence and school grades. *Intelligence, 54*, 55–69. https://doi.org/10.1016/j.intell.2015.11.004

Kurzweil, R. (2005). *The singularity is near: When humans transcend biology*. Viking.

McGrew, K. S. (2005). The Cattell-Horn-Carroll theory of cognitive abilities. In D. P. Flanagan & P. L. Harrison (Eds.), *Contemporary intellectual assessment: Theories, tests, and issues* (2nd ed., pp. 136–181). Guilford Press.

OECD. (2014). *PISA 2012 results. Creative problem solving: Students' skills in tackling real-life problems* (V ed.). OECD Publishing. https://doi.org/10.1787/9789264208070-en

Plato. (1985). *The state (Politeia)* (K. Vretska, Trans.). Reclam.

Putz-Osterloh, W. (1981). Über die Beziehung zwischen Testintelligenz und Problemlöseerfolg [On the relationship between test intelligence and problem-solving success]. *Zeitschrift für Psychologie, 189*, 79–100.

Ramalingam, D., Philpot, R., & McCrae, B. (2017). The PISA 2012 assessment of problem solving. In B. Csapó & J. Funke (Eds.), *The nature of problem solving: Using research to inspire 21st century learning* (pp. 75–91). OECD Publishing. https://doi.org/10.1787/9789264273955-7-en

Ree, M. J., & Earles, J. A. (1993). g is to psychology what carbon is to chemistry. A reply to Sternberg and Wagner, McClelland, and Calfee. *Current Directions in Psychological Science, 2*(1), 11–123. https://doi.org/10.1111/1467-8721.ep10770509

Rudin, C. (2019). Stop explaining black box machine learning models for high stakes decisions and use interpretable models instead. *Nature Machine Intelligence, 1*(5), 206–215. https://doi.org/10.1038/s42256-019-0048-x

Schneider, W. J., & McGrew, K. S. (2012). The Cattell-Horn-Carroll model of intelligence. In D. P. Flanagan & P. L. Harrison (Eds.), *Contemporary intellectual assessment, theories, tests, and issues* (3rd ed., pp. 99–145). Guilford Press.

Stern, E., & Neubauer, A. C. (2016). Intelligenz: Kein Mythos, sondern Realität [Intelligence: Not a myth, but a reality]. *Psychologische Rundschau, 67*(1), 15–27. https://doi.org/10.1026/0033-3042/a000290

Stern, W. (1912). *The psychological method of intelligence testing and its application to school children*. Johann Ambrosius Barth.

Sternberg, R. J. (1996). *Successful Intelligence: How practical and creative intelligence determine success in life*. Simon & Schuster.

Sternberg, R. J. (2016). Groundhog Day: Is the field of human intelligence caught in a time warp? A comment on Kovacs and Conway. *Psychological Inquiry, 27*(3), 236–240. https://doi.org/10.1080/1047840X.2016.1156504

Sternberg, R. J. (Ed.). (2018). *The nature of human intelligence*. Cambridge University Press. https://doi.org/10.1017/9781316817049

Sternberg, R. J. (2019). A theory of adaptive intelligence and its relation to general intelligence. *Journal of Intelligence, 7*(4), 1–17. https://doi.org/10.3390/jintelligence7040023

Sternberg, R. J. (2021). *Adaptive intelligence. Surviving and thriving in times of uncertainty*. Cambridge University Press.

Sternberg, R. J., & Kaufman, S. B. (Eds.). (2011). *The Cambridge handbook of intelligence*. Cambridge University Press. https://doi.org/10.1017/CBO9780511977244

Tuchman, B. W. (1984). *The march of folly. From Troy to Vietnam*. Ballantine Books.

Wilhelm, O., & Schroeders, U. (2019). Intelligence. In R. J. Sternberg & J. Funke (Eds.), *The psychology of human thought: An introduction* (pp. 255–275). Heidelberg University Publishing. https://books.ub.uni-heidelberg.de/index.php/heiup/catalog/book/470

Terman, L. M., & Oden, M. H. (1947). *The gifted child grows up: Twenty-five years' follow-up of a superior group*. Stanford University Press.

Joachim Funke has been Professor of General and Theoretical Psychology at the Department of Psychology of Heidelberg University since 1997. He received his doctorate from Trier University in 1984. In 1990, he habilitated at the Bonn University. Funke has been a visiting professor at various universities, including Fribourg (Switzerland), Melbourne (Australia), Nanjing (China), and Szeged (Hungary). His primary research interests are in thinking, creativity, and problem solving. His research ideas have been financially supported by the German Research Foundation, federal ministries, and the European Union, among others. Funke has published numerous articles in international journals, contributed chapters to textbooks, and has edited and published books. From 2010 to 2014, he chaired the International Expert Commission on Problem Solving in the OECD's global PISA studies. He is credited with a shift in the understanding of problem-solving that shifts

the perspective from static to dynamic problem-solving activities. In 2015, he was awarded an honorary doctorate by the Hungarian University of Szeged for his contributions to the computer-based assessment of problem solving processes. From October 2011 to March 2019, Funke served as speaker of the university's Academic Senate. His retirement began in April 2019.

Chapter 8
Interpersonal Intelligence

Sabine C. Herpertz

Abstract Interpersonal intelligence was conceived against the background of Gardner's theory of multiple intelligences. Even though it was never empirically validated, essential aspects can be found in the popular concept of "emotional intelligence" as well as in the modern empathy concept based on neuroscience. All the concepts mentioned distinguish between a (meta)cognitive and an emotional component. The former refers to processes of reflective perspective-taking, i.e., the ability to inferentially attribute mental states to others and to anticipate them. This ability, which is closely linked to executive thinking functions and linguistic expressiveness, is also referred to as "theory-of-mind" or mentalization. The emotional component refers to processes of sharing emotions, i.e., reflexive–intuitive empathy, in which emotion recognition and emotion mirroring are involved. The former ability is represented in phylogenetically younger cortical midline structures and temporoparietal areas, the latter ability in evolutionarily earlier developed areas of, among others, the sensorimotor cortex and the anterior insular region, which are also involved in the case of one's own experience of emotions. Both abilities are learned in close interaction with early caregivers; processes of divided attention, as can already be observed in toddlers, develop further into mentalization abilities, processes of mirroring and imitating affective and sensorimotor states up into intuitive, embodied understanding of the emotions of others. The measurement of Interpersonal Intelligence performance is now widely used in professional assessment procedures, not only for the medical profession. Empathy training is a psychotherapeutic technique for those psychological disorders in which a lack of empathy leads to significant problems in everyday interpersonal life.

S. C. Herpertz (✉)
Department of General Psychiatry, Center for Psychosocial Medicine, Medical Faculty of the University of Heidelberg, Heidelberg, Germany
e-mail: sabine.herpertz@uni-heidelberg.de

R. M. Holm-Hadulla et al. (eds.), *Intelligence - Theories and Applications*,
https://doi.org/10.1007/978-3-031-04198-3_8

1 Introduction and Explanation of Terms

The concept of interpersonal intelligence was founded by Howard Gardner (1983) as part of the theory of multiple intelligences (Rost, 2008). It encompasses nine facets: linguistic–linguistic, logical–mathematical, musical–rhythmic, visual–spatial, bodily–kinesthetic, naturalistic, interpersonal, and intrapersonal intelligence. Gardner's concern was to describe abilities that influence success in life, including career success. Interpersonal intelligence in this theory is conceptualized close to David Wechsler and Edward Lee Thorndike's construct of "social intelligence" (Scheibel, 2004), but also close to the modern concept of empathy (Decety et al., 2016) and means the ability to empathically understand motives, feelings, and intentions of others and to influence their moods and emotions. It should be noted that the concept of interpersonal intelligence has never been empirically validated.

The further development of components of intelligence beyond mathematical and verbal abilities led to the construct of emotional intelligence, which is still very current today. This was operationalized by Peter Salovey and John D. Mayer (1990) and brings together aspects of interpersonal and intrapersonal intelligence (understanding and influencing one's own feelings, drives, motives, and mental states) by encompassing a variety of skills not only in dealing with other people but also with oneself. The construct of Emotional Intelligence has been empirically studied on the basis of the Mayer-Salovey-Caruso Emotional Intelligence Test (MSCEIT; Mayer et al., 2002) and describes the ability to correctly perceive, understand, and influence one's own and others' feelings. It distinguishes four areas: (1) Perception of emotions: Ability to correctly recognize emotions in facial expressions, gestures, posture, and voice of others; (2) Use of emotions: Knowledge of the connections between one's own and others' emotions and thoughts, especially in the context of problem solving; (3) Understanding emotions: Ability to analyze emotions and identify them in more complex affective states, assess their changeability and understand their consequences; and finally (4) Influencing emotions: Ability to regulate own emotions, e.g., through avoidance, suppression and reappraisal, but also to change the emotions of others. Even though the construct of Emotional Intelligence is more recognized in intelligence research than that of Interpersonal Intelligence, not least because of high test score criteria, the debate as to whether it is a subconstruct of intelligence remains open. On the one hand, the construct measured by the MSCEIT has little overlap with other sub-intelligences, thus indicating sufficient discriminative validity; on the other hand, low correlations with the classical intelligence factors raise the question of whether emotional intelligence is a sub-factor of an overarching, inherently coherent concept of intelligence. With ongoing discussion in intelligence research circles, the concept of Emotional Intelligence went out of favor; however, with the publication of the rather popular book "Emotional intelligence. Why it can matter more than IQ" (Goleman, 1996), the term had already entered everyday language.

Another construct related to Interpersonal and Emotional Intelligence is that of Emotional Competence, which was not conceptualized by its founder Heiner

Rindermann as a facet of the intelligence construct, which in his view primarily describes cognitive abilities. The Emotional Competence Questionnaire (EKF, Rindermann, 2009) he developed subsumes the following four abilities: (1) recognizing one's own feelings, (2) recognizing the feelings of others, (3) emotion regulation, and (4) emotion expression.

If we look at current related constructs in the neurosciences, we find an interesting parallel in the Research Domain Criteria (RDoC; Walter, 2017) of the American National Institute of Mental Health (NIMH). Their domain of "Social Processes" includes the ability to (1) recognize nonverbal communication based on facial expressions, but also gestures, prosody, etc., (2) to adequately use nonverbal communication channels oneself, (3) To recognize oneself as an agent of one's own actions and thoughts, (4) to be able to understand and evaluate one's own mental states, and finally (5) To understand the mental states (emotions, opinions, intentions, motives, etc.) of others and thereby being able to predict and interpret their behavior. The RDoC research approach aims to integrate different levels of information from the molecular level of the genome to the systemic level of brain networks (as measured by cerebral imaging), to behavior (as reflected in behavioral observation and self-assessment) to describe and assess human functioning and functional impairments.

2 Development of Interpersonal Intelligence: A Neuroscientific View

High interpersonal intelligence requires interest in social interaction and social engagement, and further includes the ability to understand and acknowledge other people's perspectives, to develop and maintain both close and mutually satisfying relationships, and to adaptively resolve conflicts with others. Accordingly, many psychological components are involved, ranging from basal processes of identification, interpretation, and response (Hermans et al., 2019) to very specific processes such as social approach and bonding, empathy, classification within a social hierarchy, and 'in/out-group' categorization (Happe & Frith, 2014).

Systemic neuroscientific research to date refers to a few fundamental domains of interpersonal intelligence; a recently published meta-analysis on differential neural networks (Schurz et al., 2021) suggests the following differentiation of facets of interpersonal intelligence: One domain includes predominantly (meta)cognitive processes, also referred to as "*theory-of-mind*" (ToM) or mentalization as a related concept. A second domain involves predominantly affective processes that mediate emotion recognition in the other and are based on empathy, i.e., sharing emotions. These affective processes can also be referred to as empathy in a narrow sense, whereas the colloquial term empathy remains vague and usually mixes the aforementioned cognitive and affective processes. A third area describes combined cognitive/affective processes. Other authors delineate a fourth domain, which is called "compassion" or also "empathic concern" in the English-language neuroscientific literature, and for which the official German translation suggests "Mitleid" (pity), but which is better described as transposing pity into caring action, in distinction to empathy in the narrow sense. "Compassion" is not an isomorphic but a complementary feeling, which is connected with concern for the other and thus with a prosocial motivation to help (Kanske et al., 2017).

Regardless of precise and not entirely uniform terminology, neuroscientific research has been able to consistently differentiate cognitive and affective processes anatomically (see Fig. 8.1).

The phylogenetically rather recent processes of ToM, mentalization, or in the model of Decety and Moriguchi (2007) called cognitive empathy are mainly represented in cortical midline structures such as medial prefrontal cortex, superior temporal sulcus, posterior cingulate, and precuneus, respectively, as well as in the temporoparietal junction. These cognitive constructs refer to the abstract ability to deduce or infer the mental states of others on the basis of reflected perspective taking (see Fig. 8.2). They make it possible to inferentially attribute mental states to others in order to understand, explain and predict their behavior—not least in their reaction to themselves (Baron-Cohen, 1995). ToM, mentalization, or cognitive empathy, whether it refers to another's emotions, thoughts, or motives, are expressions of higher, executive thinking functions, including the ability to express oneself and others' mental states in language. If the ToM nomenclature is chosen, cognitive ToM, which refers to the attribution of cognitive mental states, and affective ToM can be further specified. Interestingly, the same structures are involved in self-referential processes, namely mentalizing or reflecting on one's own emotional and motivational states. Such common anatomical structures corroborate the constructs

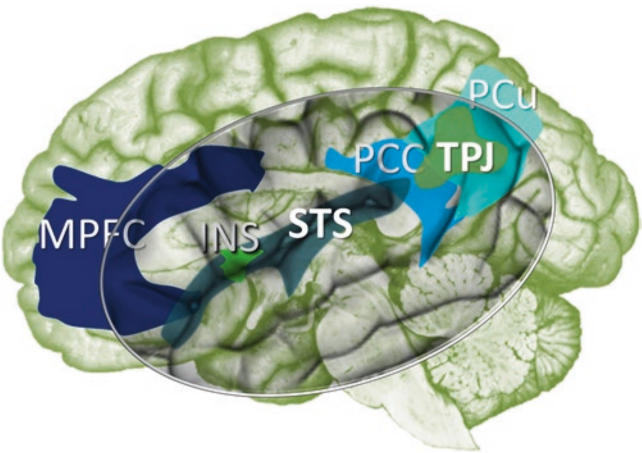

Fig. 8.1 Brain areas mediating cognitive and emotional empathy: *mPFC* medial prefrontal cortex, *INS* insula, *STS* superior temporal sulcus, *PCC* posterior cingulate cortex, *TPJ* temporoparietal junction, *PCu* precuneus

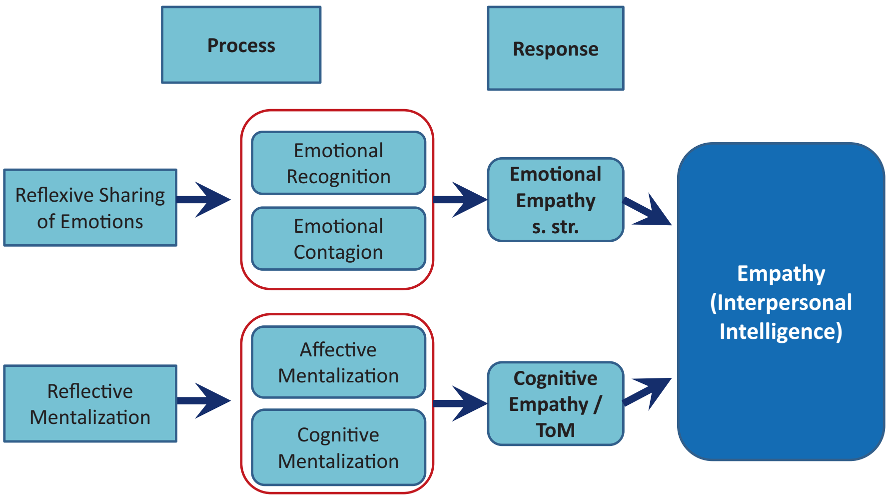

Fig. 8.2 Emotional and cognitive components of empathy (as a construct related to interpersonal intelligence)

of Emotional Intelligence and Emotional Competence, which conceptualize self- and interpersonal functions as subfacets of one construct.

According to Decety and Moriguchi (2007), emotional empathy or empathy in the narrow sense refers to an evolutionarily early process of reflexive intuitive empathy and sharing of the emotions of others (see Fig. 8.2). It presupposes the ability to recognize emotions in others (primarily based on facial expressions) and is based on the automatic imitation of affective and sensorimotor states. Anatomically, it is localized in, among others, premotor regions, areas of the sensorimotor cortex, the inferior parietal lobule, and the anterior insular region up to the supramarginal gyrus. These are the same neural networks that are involved in the case of one's own experience of emotion. Emotional empathy requires a functioning regulatory mechanism so that the individual is always aware that it is the other person's emotion and not their own. If this is not successful, the phenomenon of emotional contagion occurs, in which the other person's emotions merge with one's own, so that the suffering of the other person also leads to the suffering of the empathic person.

"Compassion" is not based on sharing emotions and is represented in a network associated with positive emotions and reward, namely ventral striatum and medial orbitofrontal cortex (Klimecki et al., 2014). Thus, it plays a distinctly different role in social life compared to emotional empathy; it includes the motivation of helping and thus an impulse to act. The differences in the importance of the two constructs are evident in physician action, which is often motivated by "compassion," whereas empathic compassion can complicate professional action if the physician is overwhelmed in their emotion regulation.

Sex differences in components of empathy have been investigated (for a review: Christov-Moore et al., 2014) and a variety of findings suggest higher empathy in the female sex, which manifests itself in better performance in emotion recognition and in the mirroring of emotions, among other things, and interestingly also in stronger emotional contagion phenomena, such as crying, in female children than in male children. Males appear to be more context-dependent and more subject to cognitive control in their empathic responses. Differences in cognitive empathy or ToM have not been adequately studied to date.

3 Development of Interpersonal Intelligence: A Look at the Early Learning History

Interpersonal intelligence takes its starting point in its neuronal representation in early relational experiences. Processes of emotional empathy or empathy in the narrow sense, which lie early in evolutionary terms, develop by way of the mirror-image imitation of affective and sensorimotor states, especially facial expressions and gestures of early caregivers (usually mother and father) from the tenth week of the infant's life (see also: Strauss & Herpertz, 2017). They are processed in the so-called mirror neuron system, which includes areas of the sensorimotor cortex, premotor regions in the anterior inferior frontal gyrus, portions of the inferior parietal lobule, and the anterior insula. According to Gallese (for review: 2007), this intuitive understanding is automatic, reflexive, and refers to an embodied ability to infer the feelings of others from the multimodal experience of one's own bodily expression, that is, one's own facial expressions and gestures. Accordingly, it is assumed that emotional empathy depends on successful early bonding experiences. During further brain development, the mirror neuron system interacts with the ventromedial prefrontal cortex and other midline structures and forms the starting point for the development of cognitive empathy or ToM. First interactive processes of this kind are found in early interactive processes of divided attention (the child follows the attentional focus of their mother with their eye movements) and then further develop in the toddler in close interaction with higher cognitive and linguistic functions (Oberwelland et al., 2016). The medial-temporal location of ToM areas maps their close relationship to autobiographical memory, i.e., experiences form the starting point of models about self and other. Thus, these are not distinct from each other; rather, a primary, "interbody relationship between the self and the other" (Fuchs & Vogeley, 2016, p. 120) is to be assumed. The primary relatedness to the other is reflected in many basal psychological functions: Thus, we holistically perceive the faces of other people, obtain relatively reliable ideas of the mental state of the other already on the basis of only vague, quickly preconceived impressions of facial expressions and gestures (Heider 1958/1977), and exert influence on him or her by directing the other's attention through our gaze behavior. Also part of later development is the adequate and sufficient ability to discriminate between one's own and other's feelings as a protection against a diffusion of self/other boundaries.

Interestingly, adequate parenting behavior that promotes the formation of Interpersonal Intelligence in the child has its neurobiological basis in networks of emotional and cognitive empathy. The first is the network that mediates emotional empathy, which in the context of parent–infant interaction means that the parent correctly processes the infant's signals and emotions, achieving synchrony of facial expressions and gestures of both interaction partners. On the other hand, it is the network responsible for cognitive empathy, which enables the parents to cognitively adopt their child's perspective and thus to understand and—especially important—to anticipate their needs. If emotional and cognitive–empathic processes work together syntonically, the infant signals, which in the infant primarily express changing levels of arousal, are reflected mimically by the early caregivers, reflected more or less consciously, and finally expressed to the infant as an understood affect in a contingent exchange (Fonagy et al., 2017). In this way, parents are able to adapt their own behavior to their child's needs and at the same time become effective as a model for learning emotion regulation, provided they have a functioning emotion regulation network (Decety & Lamb, 2006), which, localized in the medial orbitofrontal cortex, is able to regulate emotions in everyday situations. A successful empathic relationship with the child requires that the parents are motivated to enter into a growing bond with their child, a process that is usually experienced as very satisfying and is processed via the core structures of the reward network (Strathearn, 2011).

In adolescents, it was shown that their emotional competence could be predicted by neural activity in parents' mentalization networks when they had to evaluate mimic emotions. The strength of this association was mediated by the activation of adolescent mentalization networks in the same task (Telzer et al., 2014). These findings support the important role that early parent–child interaction plays in the acquisition of emotional intelligence in the next generation; the adolescent child retrieves internal representations of parental emotion processes formed in synchrony with early caregivers and through learning from the model.

4 How Is Interpersonal Intelligence Measured?

The measurement of Emotional and Interpersonal Intelligence is a component of many assessments in vocational selection procedures as well as in selection procedures for study ability in degree programs with limited admission. A wide range of test procedures are used here, ranging from personality tests for the self-description of emotional intelligence (*Trait Emotional Intelligence Questionnaire* [TEIQue]; Petrides & Furnham, 2009), performance tests (such as the *Mayer-Salovey-Caruso Emotional Intelligence Test* [MSCEIT]; Mayer et al., 2002) or *Situational Judgement Tests* (SJTs; Stemler & Sternberg, 2006) to interaction observations, such as the *Multiple Mini-Interviews (*MMIs) (Eva et al., 2004). Self-report measures may also include the *Interpersonal Reactivity Inventory* (IRI) (Davis, 1983), which measures perspective taking or cognitive empathy, emotional empathy, “compassion,” and personal suffering (through emotional contagion).

SJTs and MMIs are increasingly used in modern assessment procedures. In SJTs, images or short videos are presented in which video-based, and less frequently also written, scenarios are depicted that are typical for the professional role (Roberts et al., 2018). In each case, the variant with the highest importance is to be selected from various suggested possible courses of action in a multiple-choice procedure. Task solving presupposes that social situations can be correctly recognized and evaluated, and that implicit as well as explicit knowledge is available of how to respond correctly to the recognized situational demands (problem-solving tasks). SJTs usually test a whole range of characteristics that are considered helpful for a professional role, including empathy and ToM skills. Interrater reliabilities are consistently high for the SJT, predictive validity is also favorable, and it is not uncommon for the SJT to be combined with MMIs for incremental validity.

If one wants to measure the components of interpersonal intelligence necessary for a specific profession, this is increasingly done through observational procedures of social interactions. Corresponding test procedures are used, for example, in the selection of physicians, because social-communicative skills are predictors of success in the medical profession. The ability to understand the patient’s experiences through perspective-taking (cognitive empathy), to recognize the patient’s emotional state (emotional empathy), to be able to communicate this understanding with the patient and to develop a motivation to help (compassion) is seen as crucial for the medical profession. In addition, the ability to regulate emotions is considered important as a protection against personal suffering (Preusche & Lamm, 2016). MMIs are skill-based selection tests that involve direct observation and subsequent assessment of behaviors that are close to everyday professional life, for example, through five role-plays between an applicant and a virtual patient, usually in objective structured clinical examination (OSCE) format. According to a meta-analysis (Pau et al., 2013), MMIs are fair, transparent, and independent of gender bias or cultural and socio-economic influences. In addition, the interrater reliability is moderate to high.

Based on the construct of emotional availability, an MMI is currently being developed in Heidelberg for the selection of medical students, which will measure components of interpersonal intelligence in applicants beyond the examination of cognitive abilities in the Test for Medical Studies (TMS). Emotional availability is understood to be an aspect of all social relationships (Biringen, 2000), which, when applied to the medical profession, means the willingness of a doctor to enter into empathic, understanding contact with their patient. Emotional availability has crucial importance in parent–child relationships and was first studied here (Oppenheim, 2012), but has also been the subject of study in therapeutic relationships (Söderberg et al., 2014) (Zeddies, 1999). Emotional availability describes the ability to recognize the emotional state, mental state, and needs of the other person, as well as to respond to them adequately, thus creating a safe emotional and cooperative conversational context. The criteria used by Herpertz (Biringen et al., 2019) developed for assessing doctor–patient interaction in applicant selection, *Interpersonal*

Competencies - Medicine (IC-M) include four subscales: Sensitivity (accepting, empathic, warm, responsive to the needs of the counterpart), Structuring (giving sufficient information, making suggestions, setting boundaries in an appropriate manner, formulating reasonable demands, resolving deadlocked conversational situations), Non-Intrusiveness (recognizing and respecting the integrity and autonomy of the counterpart), and Non-Hostility (overt or covert hostility, especially in stressful situations). The raters are asked to pay attention to general behavior patterns and verbal as well as non-verbal emotional signals in communication episodes of 5 min. Specifically required are attentiveness to social signals, congruent (appropriate, empathetic) affect with the patient's communications, ability to adopt perspective or ToM capacity, emotional empathy with clear self/other differentiation, creativity, structuring ability, and stress tolerance. This MMI, which is currently being tested with regard to various quality criteria, will be used for the first time in the selection of the 2022 rural doctor quota (cf. Rural Doctor Act 2021). Finally, psychophysiological measures will be added, such as electromyographic activity of mimic muscles and physiological synchrony (peripheral and central) between transmitter and receiver.

5 Interpersonal Intelligence and Personality Disorders

Disturbances or impairments of interpersonal and emotional intelligence are found in a number of mental illnesses. They are particularly prominent features of personality disorders, especially borderline and antisocial personality disorder. The interpersonal dysfunction formulated in ICD-11 as a crucial diagnostic feature is about the inability to form and shape relationships in an empathic and cooperative way (Herpertz, 2018).

In patients with borderline personality disorder, particularities in emotional empathy are found together with a lack of cognitive empathy or impaired ToM functions (Herpertz et al., 2018). In tasks in which patients were asked to rate facial emotions as accurately and quickly as possible, negativity bias was consistently reported, especially in the way that affected individuals experience neutral faces as threatening and rejecting (Izurieta Hidalgo et al., 2016). Affected individuals showed decreased activity of the superior temporal sulcus and temporoparietal junction while solving affective ToM tasks, i.e., recognizing others' feelings from their facial expressions and against the background of the situational context (Dziobek et al., 2011; Mier et al., 2013). Impairments in ToM processes are not so much reflected in a simple lack of perspective taking, but rather in distorted and rigid interpretations of the emotions and motives of others, which in borderline personality disorder is also referred to as a tendency to hypermentalization (Sharp et al., 2013) and is the starting point for many misunderstandings in the interpersonal context. When instructed to perceive their own feelings while watching other people suffer, i.e., emotional-empathic processes were activated, they showed higher activity in the insula and this was associated with increased autonomic arousal and their own attribution of increased negative emotions (Dziobek et al., 2011). Underlying this is the tendency of patients with borderline personality disorder to share other people's emotions, which on the one hand is expressed—often positively sanctioned—in sympathy and compassion, but on the other hand entails the danger of irritating emotional contagion phenomena up to the diffusion of self/alien boundaries (Ripoll et al., 2013; Jeung & Herpertz, 2014).

Differentially different facets of interpersonal intelligence are affected in antisocial, psychopathic individuals (Herpertz et al., 2018). So-called "psychopaths" have unimpaired cognitive–empathic abilities, i.e., they can anticipate the emotions and intentions of other people by adopting perspective and use these insights for their own goals. With regard to emotional empathy, on the other hand, there are findings that point to impairments in emotion recognition, especially of fearful but also sad and happy affects (Dawel et al., 2012; Timmermann et al., 2017). Impaired recognition of fearful faces correlates with the personality trait callousness. Interestingly, imaging findings in prisoners with psychopathic traits also showed reduced neural activity in the "fusiform face area" and other face-processing brain areas, such as the superior temporal sulcus, when asked to recognize dynamically changing fearful, sad, and happy facial movements (Decety et al., 2014). When "psychopaths" are confronted with other people's suffering, they show reduced activity in the emotional empathy network (Seara-Cardoso et al., 2016). In another study, lower neural activity in the ventromedial prefrontal cortex, orbitofrontal cortex, amygdala, and anterior cingulate compared to controls correlated with the reduced compassion for pain and suffering of others observed in them (Seara-Cardoso et al., 2016). Studies by Decety et al. (2015) on "psychopaths" further sought to distinguish between empathy and the motivational drive to turn this feeling into a caring impulse to act. They were able to show that only electrophysiological correlates corresponding to a caring action drive differed from controls, but not brain potentials associated with compassion. These electrophysiological findings fit with those from fMRI studies, which showed that when explicitly instructed to be compassionate, individuals with psychopathic traits are perfectly capable of activating the emotional empathy network. It is hypothesized that deviations in the attention of psychopathic individuals in the sense of a bottleneck phenomenon ("theory of the bottleneck") undermine their sensitivity to emotion-related cue stimuli; thus, dysfunctional attentional processes underlie psychopathy (Baskin-Sommers et al., 2011). The issue of dysfunction in empathic abilities in psychopaths may not be described as a simple deficiency phenomenon, but could be rooted in specifics of salience experience, i.e., in the perception of psychopaths social stimuli do not "jump out" from the multitude of stimuli. In everyday situations, this leads to the fact that the needs of others receive less attention than the assertion of one's own goals, i.e., attention is neglected.

6 Outlook

Can interpersonal intelligence be trained? Such training could make a lot of sense, either in terms of professional empowerment or as an intervention for people in whom a lack of cognitive and/or emotional empathy has acquired disease value. The former has been integrated into undergraduate medical courses in recent years, they learn cognitive and emotional empathy as well as the ability to regulate their own emotions and thus avoid personal suffering by role-playing with drama patients. Empathy and "compassion" training has also been studied neuroscientifically for its effectiveness. The aims of a short, 3 ⇥ 60 min empathy training (Riess et al., 2012) were to improve mindfulness of patients' verbal and non-verbal emotional communication, including exercises to improve recognition of subtle mimic signals, to improve empathic understanding through perspective taking, and to increase emotional and physiological self-care and emotion regulation. Compassion was trained by way of contemplative techniques (Klimecki et al., 2014). Both training components led to improvements in Interpersonal Intelligence as well as activation changes in the brain networks outlined above. It remains to be seen whether an improvement in empathy and compassion can indeed be successfully transferred from the laboratory context to everyday interpersonal life.

Reference

Baron, J. H. (2009). Sailors' scurvy before and after James Lind - A reassessment. *Nutrition Reviews, 67*(6), 315–332. Retrieved from https://academic.oup.com/nutritionreviews/article/67/6/315/1807435

Baron-Cohen, S. (1995). *Mindblindness*. MIT Press.

Baskin-Sommers, A. R., Curtin, J. J., & Newman, J. P. (2011). Specifying the attentional selection that moderates the fearlessness of psychopathic offenders. *Psychological Science, 22*(2), 226–234.

Biringen, Z., Benjamin, E., Mayer, B., Fuchs, A., & Herpertz, S. C. (2019). *Emotional Availability (EA) Scales. Manual for Medical Doctor-Patient Relationship (EASMD)*. Not published.

Biringen, Z. (2000). Emotional availability: Conceptualization and research findings. *The American Journal of Orthopsychiatry, 70*(1), 104–114.

Christov-Moore, L., Simpson, E. A., Coude, G., Grigaityte, K., Iacoboni, M., & Ferrari, P. F. (2014). Empathy: Gender effects in brain and behavior. *Neuroscience and Biobehavioral Reviews, 46*(Pt 4), 604–627.

Davis, M. H. (1983). Measuring individual differences in empathy: Evidence for a multidimensional approach. *Journal of Personality and Social Psychology, 44*(1), 113.

Dawel, A., O'Kearney, R., McKone, E., & Palermo, R. (2012). Not just fear and sadness: Meta-analytic evidence of pervasive emotion recognition deficits for facial and vocal expressions in psychopathy. *Neuroscience and Biobehavioral Reviews, 36*(10), 2288–2304.

Decety, J., Bartal, I. B., Uzefovsky, F., & Knafo-Noam, A. (2016). Empathy as a driver of prosocial behavior: Highly conserved neurobehavioural mechanisms across species. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences, 371*(1686), 20150077.

Decety, J., & Lamb, C. (2006). Human empathy through the lens of social neuroscience. *ScientificWorldJournal, 6*, 1146–1163.

Decety, J., Lewis, K. L., & Cowell, J. M. (2015). Specific electrophysiological components disentangle affective sharing and empathic concern in psychopathy. *Journal of Neurophysiology, 114*(1), 493–504.

Decety, J., & Moriguchi, Y. (2007). The empathic brain and its dysfunction in psychiatric populations: Implications for intervention across different clinical conditions. *Biopsychosocial Medicine, 1*, 22.

Decety, J., Skelly, L., Yoder, K. J., & Kiehl, K. A. (2014). Neural processing of dynamic emotional facial expressions in psychopaths. *Social Neuroscience, 9*(1), 36–49.

Dziobek, I., Preissler, S., Grozdanovic, Z., Heuser, I., Heekeren, H. R., & Roepke, S. (2011). Neural correlates of altered empathy and social cognition in borderline personality disorder. *Neuroimage, 57*(2), 539–548.

Eva, K. W., Rosenfeld, J., Reiter, H. I., & Norman, G. R. (2004). An admissions OSCE: The multiple mini-interview. *Medical Education, 38*(3), 314–326.

Fonagy, P., Luyten, P., Allison, E., & Campbell, C. (2017). What we have changed our minds about: Part 2. Borderline personality disorder, epistemic trust and the developmental significance of social communication. *Borderline Personality Disorder and Emotion Dysregulation, 4*, 9.

Fuchs, T., & Vogeley, K. (2016). Self-experience and Self-disorders. In S. C. Herpertz, F. Caspar, & K. Lieb (Eds.) *Psychotherapy: Function and Disorder Related Approach*. Elsevier: 215–231.

Gallese, V. (2007). Before and below 'theory of mind': Embodied simulation and the neural correlates of social cognition. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences, 362*(1480), 659–669.

Gardner, H. (1983). *The theory of multiple intelligences*. Heinemann.

Goleman, D. (1996). Emotional intelligence. Why it can matter more than IQ. *Learning, 24*(6), 49–50.

Happe, F., & Frith, U. (2014). Annual research review: Towards a developmental neuroscience of atypical social cognition. *Journal of Child Psychology and Psychiatry, 55*(6), 553–557.

Heider, F. (1977). *Psychology of interpersonal relationships*. (Original book published, *The Psychology of Interpersonal Relations*. Lawrence Erlbaum Associates, 1958). Klett Verlag.

Hermans, K., Achterhof, R., Myin-Germeys, I., Kasanova, Z., Kirtley, O., & Schneider, M. (2019). Improving ecological validity in research on social cognition. In *Social cognition in psychosis* (pp. 249–268).

Herpertz, S. C. (2018). A new approach to classifying personality disorders. *Fortschritte der Neurologie-Psychiatrie, 86*(3), 150–155.

Herpertz, S. C., Bertsch, K., & Jeung, H. (2018). Neurobiology of criterion A: Self and interpersonal personality functioning. *Current Opinion in Psychology, 21*, 23–27.

Izurieta Hidalgo, N. A., Oelkers-Ax, R., Nagy, K., Mancke, F., Bohus, M., Herpertz, S. C., & Bertsch, K. (2016). Time course of facial emotion processing in women. With borderline personality disorder: An ERP study. *Journal of Psychiatry & Neuroscience, 41*(1), 16–26.

Jeung, H., & Herpertz, S. C. (2014). Impairments of interpersonal functioning: Empathy and intimacy in borderline personality disorder. *Psychopathology, 47*(4), 220–234.

Kanske, P., Bockler, A., & Singer, T. (2017). Models, mechanisms and moderators dissociating empathy and theory of mind. *Current Topics in Behavioral Neurosciences, 30*, 193–206.

Klimecki, O. M., Leiberg, S., Ricard, M., & Singer, T. (2014). Differential pattern of functional brain plasticity after compassion and empathy training. *Social Cognitive and Affective Neuroscience, 9*(6), 873–879.

Mayer, J. D., Salovey, P., & Caruso, D. R. (2002). *Mayer-Salovey-Caruso emotional intelligence test (MSCEIT) item booklet*.

Mier, D., Lis, S., Esslinger, C., Sauer, C., Hagenhoff, M., Ulferts, J., Gallhofer, B., & Kirsch, P. (2013). Neuronal correlates of social cognition in borderline personality disorder. *Social Cognitive and Affective Neuroscience, 8*(5), 531–537.

Oberwelland, E., Schilbach, L., Barisic, I., Krall, S. C., Vogeley, K., Fink, G. R., Herpertz-Dahlmann, B., Konrad, K., & Schulte-Ruther, M. (2016). Look into my eyes: Investigating joint attention using interactive eye-tracking and fMRI in a developmental sample. *NeuroImage, 130*, 248–260.

Oppenheim, D. J. D. (2012). Emotional availability: Research advances and theoretical questions. *Development and Psychopathology, 24*(1), 131–136.

Pau, A., Jeevaratnam, K., Chen, Y. S., Fall, A. A., Khoo, C., & Nadarajah, V. D. (2013). The Multiple Mini-Interview (MMI) for student selection in health professions training - a systematic review. *Medical Teacher, 35*(12), 1027–1041.

Petrides, K., & Furnham, A. (2009). *Trait emotional intelligence questionnaire (TEIQue), technical manual*. London Psychometric Laboratory.

Preusche, I., & Lamm, C. (2016). Reflections on empathy in medical education: What can we learn from social neurosciences? *Advances in Health Sciences Education: Theory and Practice, 21*(1), 235–249.

Riess, H., Kelley, J. M., Bailey, R. W., Dunn, E. J., & Phillips, M. (2012). Empathy training for resident physicians: A randomized controlled trial of a neuroscience-informed curriculum. *Journal of General Internal Medicine, 27*(10), 1280–1286.

Rindermann, H. (2009). *Emotional Competence Questionnaire: EKF; Assessment of emotional competencies and emotional intelligence from the perspective of self and others*. Hogrefe.

Ripoll, L. H., Snyder, R., Steele, H., & Siever, L. J. (2013). The neurobiology of empathy in borderline personality disorder. *Current Psychiatry Reports, 15*(3), 344.

Roberts, C., Khanna, P., Rigby, L., Bartle, E., Llewellyn, A., Gustavs, J., Newton, L., Newcombe, J. P., Davies, M., Thistlethwaite, J., & Lynam, J. (2018). Utility of selection methods for specialist medical training: A BEME (best evidence medical education) systematic review. BEME guide no. 45. *Medical Teacher, 40*(1), 3–19.

Rost, D. H. (2008). Multiple intelligences, multiple irritations. *Journal of Educational Psychology, 22*(2), 97–112.

Salovey, P., & Mayer, J. D. (1990). Emotional intelligence. *Imagination, Cognition and Personality, 9*(3), 185–211.

Scheibel, S. (2004). *Social and emotional intelligence concept: History, facets, measurement*. GRIN Verlag.

Schurz, M., Radua, J., Tholen, M. G., Maliske, L., Margulies, D. S., Mars, R. B., Sallet, J., & Kanske, P. (2021). Toward a hierarchical model of social cognition: A neuroimaging meta-analysis and integrative review of empathy and theory of mind. *Psychological Bulletin, 147*, 293.

Seara-Cardoso, A., Sebastian, C. L., Viding, E., & Roiser, J. P. (2016). Affective resonance in response to others' emotional faces varies with affective ratings and psychopathic traits in amygdala and anterior insula. *Social Neuroscience, 11*(2), 140–152.

Sharp, C., Ha, C., Carbone, C., Kim, S., Perry, K., Williams, L., & Fonagy, P. (2013). Hypermentalizing in adolescent inpatients: Treatment effects and association with borderline traits. *Journal of Personality Disorders, 27*(1), 3–18.

Söderberg, A. K., Elfors, C., Larsson, M. H., Falkenström, F., & Holmqvist, R. J. P. R. (2014). Emotional availability in psychotherapy: The usefulness and validity of the Emotional Availability Scales for analyzing the psychotherapeutic relationship. *Psychotherapy Research, 24*(1), 91–102.

Stemler, S. E., & Sternberg, R. J. (2006). Using situational judgment tests to measure practical intelligence. *Situational Judgment Tests: Theory, Measurement, and Application* 107–131.

Strathearn, L. (2011). Maternal neglect: Oxytocin, dopamine and the neurobiology of attachment. *Journal of Neuroendocrinology, 23*(11), 1054–1065.

Strauss, B., & Herpertz, S. C. (2017). Attachment, empathy, intersubjectivity. In S. C. Herpertz, F. Caspar & K. Lieb (Eds.), *Psychotherapy: functioning and disorders approach*. Elsevier: 215–231.

Telzer, E. H., Qu, Y., Goldenberg, D., Fuligni, A. J., Galvan, A., & Lieberman, M. D. (2014). Adolescents' emotional competence is associated with parents' neural sensitivity to emotions. *Frontiers in Human Neuroscience, 8*, 558.

Timmermann, M., Jeung, H., Schmitt, R., Boll, S., Freitag, C. M., Bertsch, K., & Herpertz, S. C. (2017). Oxytocin improves facial emotion recognition in young adults with antisocial personality disorder. *Psychoneuroendocrinology, 85*, 158–164.

Walter, H. (2017). Research domain criteria (RDoC): Psychiatric research as applied cognitive neuroscience. *Nervenarzt, 88*(5), 538–548.

Zeddies, T. J. (1999). Becoming a psychotherapist: The personal nature of clinical work, emotional availability and personal allegiances. *Psychotherapy, 36*(3), 229.

Sabine C. Herpertz studied medicine in Bonn, obtained her doctorate in Frankfurt a.M., and habilitated in psychiatry and psychotherapy at RWTH Aachen. She is a specialist in psychiatry and psychotherapy, neurology, and psychotherapeutic medicine. She held a professorship in Experimental Psychopathology at RWTH Aachen University between 2002 and 2003, before becoming Chair of Psychiatry and Psychotherapy at the University of Rostock between 2003 and 2009. Since 2009, she has been Chair of General Psychiatry at Heidelberg University Hospital and Medical Director of the eponymous clinic. Since 2018, she has been Dean of Studies at the Heidelberg Medical Faculty.

Chapter 9
Development of Intelligence in the Context of Digital Media Use

Katajun Lindenberg and Ulrike Basten

Abstract Psychological research is increasingly concerned with the interactions between the use of digital games and the development of intelligence in children and adolescents. This paper integrates the findings of neurocognitive research on effects of gaming on attentional processes and executive functions as well as the findings of clinical psychological studies on cognitive consequences of addictive gaming. For specific cognitive abilities such as processing speed, attentional control, and spatial cognition, positive effects of video games are well documented. Media multitasking, on the other hand, is associated with weaker executive functions and impairs performance in tasks performed in parallel. Frequent gaming leads to structural changes in the mesolimbic reward system that are similar to those found in people with addicted video game use. Such brain structural changes are associated with sensitization of the reward system and maintenance of addictive computer game behavior, which is associated with developmental decline and reduced academic performance. To integrate findings from the fields of cognition and addiction, we present a model of the reciprocal influence of intelligence and media use in which attentional control, reward sensitivity, and a decision-making process that weighs expected positive against possible negative behavioral consequences are postulated as mediating factors. We hypothesize that high reward sensitivity and low attentional control represent risk factors for adverse media use behaviors that include unproductive media multitasking, excessive gaming and addictive video game use, and performance decrements due to neglect of other life domains (school, college, work). On the other hand, moderate reward sensitivity and a high ability to control attention represent protective factors that favor the controlled and purposeful use of digital media. We assume that intelligence plays an important role in the individual pattern of media use and its consequences.

K. Lindenberg (✉)
Department of Child and Adolescent Psychotherapy, Institute of Psychology, Goethe University Frankfurt, Frankfurt, Germany
e-mail: lindenberg@psych.uni-frankfurt.de

U. Basten
Department of Psychology, University of Koblenz-Landau, Mainz, Germany
e-mail: basten@uni-landau.de

R. M. Holm-Hadulla et al. (eds.), *Intelligence - Theories and Applications*,
https://doi.org/10.1007/978-3-031-04198-3_9

1 Introduction

The availability of digital media has increased considerably in the past two decades. Among children and adolescents, clinical psychological research on Internet use disorders focuses on the use of video games in particular. In 2020, adolescents in Germany spent an average of 258 min a day—i.e., more than 4 h a day—online (Medienpädagogischer Forschungsverbund Südwest, 2020). After friendships (with 93% agreement), the smartphone is named as the most prevalent interest of 6- to 13-year-old children with 69% agreement, on a par with sports (Medienpädagogischer Forschungsverbund Südwest, 2018). By the transition to secondary school, most children own their own mobile phone or smartphone, with 96% of 12- to 19-year-olds already doing so. A fixed games console (e.g., Xbox, Playstation, Wii, or Switch) is owned by 70% of young people (Medienpädagogischer Forschungsverbund Südwest, 2020). The use of digital games has been given a prominent place in the everyday lives of children and young people and is considered an entertaining pastime. This raises the intriguing question of how the frequent use of modern media affects our cognitive functions and their development, and conversely, how intelligence affects the functional use of media. Psychological research on this question has focused particularly on attentional processes and executive functions, as well as developmental impairments caused by addictive video game use. In terms of cognitive development, research has focused on the potential effects of (a) video games (especially action video games) and (b) media multitasking on attentional processes and executive functions. This chapter provides an overview of both areas of research and also addresses the importance of addictive video game use for cognitive development.

2 Influence of Video Games on Cognitive Development

The effects of video games on cognitive development and cognitive abilities have been researched for about 30 years now. It is necessary to distinguish different types of video games (*genres*) in this research. For example, one does not expect the same effects for first-person shooter as for strategy games. Different genres are distinguished in the field of video games, e.g., action games, sports and racing games, strategy games, role-playing games, etc. However, these genres are not sharply distinguished from each other and are not uniformly defined (Faisal & Peltoniemi, 2018). Moreover, in recent years, the traditional genres seem to be merging more and more in hybrid formats of video games (Dale & Green, 2017).

Early studies in the 1990s suggested that video games could lead to improvements in cognitive functions. As little as 6 h of play with the video game Tetris led to improvements in performance on independent mental rotation and spatial visualization tasks in adolescents with no prior video game experience that were greater than in adolescents who had not played Tetris in the study (Okagaki & Frensch, 1994). This finding suggested that video games may represent a type of intensive cognitive training for which there may be transfer to other tasks assessing cognitive functions. The early studies of the 1990s have been followed by many others that have examined the relationship between video game experience and cognitive function. Many of these studies have been cross-sectional correlational studies. These studies typically found a moderate but well-replicated positive association between individual levels of experience with video games (especially action video games) and performance on laboratory tests of attentional functions (Bavelier & Green, 2019). Individuals who play video games frequently and for long periods of time in their free time (*gaming*) show better performance in several cognitive functions, particularly processing speed, attentional control, and spatial cognition (Bediou et al., 2018).

While the relationship between video game experience and cognitive functions, in particular attentional functions, is well documented in cross-sectional studies, the correlative approach of these studies does not allow us to draw conclusions about the underlying causes. It could be that experience with video games causally alters individual information processing (in the sense of cognitive training) in such a way that improved attentional abilities result. Conversely, the findings could also be explained by individuals with better attention control skills simply being better suited to playing video games. They are better able to cope with the demands of the games and therefore enjoy playing more and stick with it longer. In addition to the possibility of a third variable influencing both variables, the cause of the relationship could also lie in an interaction of the two factors. In this case, this would mean that attention skills and video game experience mutually reinforce each other.

Intervention studies in which individuals with no—or very little—video game experience play video games to a certain extent as part of a study, and improvements in cognitive performance from a pre-video game test to a post-training test are compared with corresponding improvements in an active control group, suggest that the association is at least partly due to the fact that video game experience does indeed have a causal effect on improving processing speed, attentional control, and spatial cognition (Bavelier & Green, 2019; Bediou et al., 2018). Across tasks and response modalities, practice in video games led to generally faster reaction times (Dye et al., 2009). The fact that individuals with video game experience did not exhibit increased error rates suggests that they are not simply responding more impulsively (Mack & Ilg, 2014). Rather, modeling of the cognitive processes underlying reaction times suggests that video game players accumulate information more quickly when deciding between response options (Green et al., 2010). In this sense, the faster reaction times of video gamers can be interpreted as an indicator of increased information processing speed.

It is also very well established that video games lead to improvements in various attentional functions (Bediou et al., 2018). While these effects were initially construed as improvements in selective attention (Green & Bavelier, 2003), they are now interpreted—even more fundamentally—as reflecting improved attentional control (Bavelier & Green, 2019; Chisholm & Kingstone, 2015). Attentional control underpins several cognitive functions that are improved in video game players—and for which intervention studies suggest that these improvements are also causally related to video game training. In particular, improved attentional control explains better performance in maintaining selective attention by focusing on goal-relevant information while inhibiting irrelevant information (Chisholm et al., 2010; Chisholm & Kingstone, 2012, 2015). Furthermore, better attentional control facilitates goal-directed switching between selective and divided attention, as well as switching between different tasks. The latter is manifested in reduced switching costs in laboratory studies of task switching (Shawn Green et al., 2012).

Finally, improvements in spatial cognition have also been observed as an effect of video games (Bediou et al., 2018). Video game play led to improved performance in spatial working memory tasks (Blacker & Curby, 2013; Wilms et al., 2013) as well as spatial attention and mental rotation (Feng et al., 2007; Spence et al., 2009). The evidence that video games causally improve attentional functions does not preclude the model, which is also intuitively plausible, that there is in fact a reciprocal positive reinforcement between gaming and attentional skills. This would mean that on the one hand higher attentional control skills make video gaming more likely, while on the other hand gaming has a positive effect on attentional skills.

The improvements in attentional functions described here have been reported particularly for the use of action video games, which place high demands on the speed of information processing. Players must respond very quickly to changing stimuli, some of which are unexpected, and adjust their behavior when conflicts arise. Attention and cognitive control must be maintained for extended periods of time and decisions must be made under time pressure. Players must attend to relevant information while suppressing processing of irrelevant information, thereby video games require orientation in 3D spaces where players must remember positions for which internal representations must be manipulated. It is assumed that a substantial load for the attentional system through perceptual, cognitive, and motor processes (*attentional load*) as well as particularly high or in the course of the game—according to the performance of the players—steadily increasing demands on a flexible control of attention are the crucial factors for the success of the games in the sense of a cognitive training, which at the same time distinguish action video games from other genres of video games.

Training through action video games is also particularly intensive because the adaptation of the level of challenge in conjunction with sophisticated reinforcement schedules binds players to gaming in the long term. At the same time, these reinforcement mechanisms are associated with an increased risk of developing a computer game disorder, which in turn can have a negative impact on cognitive development (see below, *Influence of addictive video game use on cognitive development*). In general, however, it must be taken into account that video games are associated with very different demands and not every video game will be associated with the improvements in cognitive abilities described here. A distinction must be made not only between different genres (see above) but even more between specific attributes and the constitutive cognitive requirements of different games (Baniqued et al., 2013; Bedwell et al., 2012).

Any form of lasting improvement in cognitive abilities can be assumed to be due to changes in the neural structures and processes underlying information processing. Indeed, gaming has been observed to lead to changes in brain structure and function that may mediate the effects on cognitive abilities (Palaus et al., 2017). In a study using the video game Super Mario, an increase in gray matter in three regions of the brain associated with spatial orientation and attentional control was observed as an effect of 2 months of training for a minimum of 30 min per day (Kühn et al., 2014). Furthermore, the ability to inhibit irrelevant distractor information, which is better developed in skilled video gamers, was associated with a reduced neuronal response to irrelevant stimuli for brain activity measured with electroencephalography (EEG; Krishnan et al., 2013; Mishra et al., 2011).

In addition to changes in brain regions primarily associated with supporting cognitive processes, changes have also been observed in the brain's mesolimbic reward system. In a sample of 14-year-olds, adolescents with more video game experience showed a larger volume of the left ventral striatum (Kühn et al., 2011). The authors speculate that this structural feature may be a correlate of altered reward processing. Studies on brain activation changes suggest that video game experience may enhance the ability to maintain reactivity of the neural reward system (Lorenz et al., 2015). Some authors attribute the potential of video games to lead to changes in brain structures and functions within a relatively short period of time (a few days or weeks) to the fact that the reward processes triggered by the games particularly stimulate neuronal plasticity, which then also facilitates the development of cognitive processing abilities (Bavelier & Green, 2019; Kilgard & Merzenich, 1998). These same processes are also discussed in models of the development and maintenance of computer game disorder (see below, *Influence of addictive video game use on cognitive development*).

3 Influence of Media Multitasking on Cognitive Development

Media multitasking describes the simultaneous use of different media. In principle, the term refers to both analogue and digital media. However, the multitude of modern digital media and media applications results in a much greater variety and thus a significantly increased potential for multitasking. Media multitasking is, for example, a pupil or student who writes an essay on the computer, does internet research in between, and answers messages in social media while the television is on in the background. Most studies measure the extent of media multitasking by the total number of media used in a typical hour of media use as reported by study participants. This includes print media, television, music, video games, telephone, text messaging, chatting, email, web surfing, and other video applications (Ophir et al., 2009).

What effect does media multitasking have on our cognitive processes and performance? This question can be broken down into two aspects: (1) the immediate effects on cognitive performance in the moment of multitasking and (2) potential long-term effects on the general way we process information. The first question can be answered very clearly based on the available studies. Media multitasking leads to an impairment of performance in the main task when media are used in parallel to a defined cognitive main task. This impairment is attributed to an additional demand on cognitive resources by multitasking, which leads to an insufficient amount of resources being available for the main task. The distribution of cognitive resources leads to impaired performance on cognitive tasks in the moment and is also reflected in lower grades in the long run. This is well documented for the use of media during classes or a lecture (e.g., video and mobile phone applications, esp. chats) as well as for media use during homework and reading in general (Bowman et al., 2010; Carrier et al., 2015; Jacobsen & Forste, 2011; Junco & Cotten, 2011; Rosen et al., 2013; Wilmer et al., 2017; Wood et al., 2012). Brain imaging studies further suggest that the neural mechanisms of learning with and without distraction from multitasking demands also differ from each other (Foerde et al., 2006). Multitasking, such as that resulting from the introduction of a secondary task in parallel with a memory task in laboratory studies, leads to impairments in declarative learning that have been associated with reduced activity in structures of the medial temporal lobe, which is important for memory encoding (Poldrack & Foerde, 2008).

However, the second question is even more interesting regarding implications for the development of cognitive abilities and the long-term shaping of information processing: Does constant exposure to a wide variety of media change the way we think? Does media multitasking (regardless of the immediate effects) lead to a fundamentally altered information processing? The idea that this could be the case could be based on the assumption that habitual media multitasking in everyday life represents a kind of cognitive training that may lead to permanently altered information processing—possibly due to altered neural processing. In terms of cognitive training, one might expect that people who do a lot of media multitasking would be trained to do many things at once and would be particularly good at switching flexibly between tasks and managing multiple cognitive demands simultaneously.

However, a first, highly regarded study on this topic led to the surprising finding that, on the contrary, a negative correlation was observed between the extent of habitual media multitasking and the ability to manage several tasks simultaneously. Individuals who self-reported frequent use of multiple media in parallel performed worse in a laboratory task on *task switching,* as well as in several other tasks assessing cognitive control functions, than individuals who engaged in little media multitasking in everyday life (Ophir et al., 2009). The authors speculated that the findings could be explained by the fact that strong media multitaskers are less able to block out irrelevant information from the environment and from memory, as well as irrelevant tasks (*task sets*). This, in turn, could be due to a bias of cognitive control functions in favor of a broad (and thus also less focused) consideration and processing of information (*breadth-biased cognitive control*; Ophir et al., 2009). Individuals who engage in pronounced media multitasking would generally operate with more bottom-up driven attentional control—while simultaneously showing weaker top-down control. The idea of a broader attentional focus was supported by further studies suggesting that strong media multitaskers take in more information from the environment than would be necessary to complete the task, even in simple attentional tasks (Cain & Mitroff, 2011).

However, subsequent studies have only partially replicated the associations of media multitasking with poorer performance on task switching and distractor inhibition reported by Ophir et al. (2009) (Uncapher & Wagner, 2018). For task switching and dual task paradigms, findings are particularly inconsistent. After the pioneer study by Ophir and colleagues suggested that media multitaskers performed worse in task-switching paradigms (showing higher reaction time costs), subsequent studies of switching ability in the laboratory are mixed with a replication (Wiradhany & Nieuwenstein, 2017), some null findings (Baumgartner et al., 2014; Minear et al., 2013), and several studies suggesting an improved ability to switch between tasks in media multitaskers (Alzahabi & Becker, 2013; Elbe et al., 2019). For working memory tasks, some studies showed poorer performance in media multitaskers, some studies reported null effects, but no study reported an advantage of multitaskers in working memory tasks (Uncapher & Wagner, 2018).

In particular, media multitaskers appear to perform worse in simple working memory tasks when the task places relatively little load on working memory. It seems as if, when the cognitive system is not working at full capacity, task-irrelevant information is also given attention and is processed. This additional irrelevant information distracts from the actual task to be processed and leads to increased errors. In their review paper, Uncapher and Wagner (2018) speculate that the reason for processing irrelevant information under low cognitive load might be that individuals who engage in heavy media multitasking exhibit poorer attentional control, which is needed to differentiate between target-relevant and -irrelevant information. Alternatively, or in addition, an even more general impairment in the maintenance of attention could underlie the performance deficits of media multitaskers. Fluctuations in the maintenance of goal-directed attention led to attentional errors or lapses (*attention lapses*) that accounted for poorer performance in laboratory tasks assessing cognitive control functions (Ralph et al., 2014, 2015; Uncapher & Wagner, 2018).

The hypothesis of less efficient attentional control in the presence of marked media multitasking is also supported by a brain imaging study in which adolescents and young adults had to complete a sentence comprehension task under different conditions of attentional focus while their brain activation was measured with functional magnetic resonance imaging (fMRI; Moisala et al., 2016). When completing the sentence comprehension task under distraction conditions, participants who reported higher levels of media multitasking showed poorer performance with concurrent stronger brain activity in lateral and medial parts of the prefrontal cortex. The greater activation of these brain areas associated with cognitive control may be interpreted as evidence of less efficient attentional control, which requires greater neural effort. Furthermore, a recent brain imaging study using fMRI suggests that an increased propensity for attentional errors and associated impaired neural processing in encoding and retrieving memory content may explain the negative association between media multitasking and long-term memory performance (Madore et al., 2020).

What are the implications of the findings described here for cognitive performance in everyday life? The "broader" processing of information resulting from a weaker top-down controlled, more bottom-up driven attention may even be an advantage for the efficient parallel processing of cognitively less demanding tasks in everyday life. For tasks such as chat communication on social media while watching movies or video clips for entertainment, less focused processing may be sufficient, and the breadth of information intake may favor responding to more stimuli in less time. However, in-depth processing, essential for understanding of complex issues and for memory formation, requires focused attention that must be sustained over a longer period of time. It allows inhibiting disturbing stimuli from the environment and irrelevant representations from memory, encoding new information into the working memory and putting relevant representations in working memory into relation. Thus, the ability to purposefully control and focus attention on a specific thing or task is an important prerequisite for success in school, training, study, and work. More generally, it is the basis for understanding and learning in general—and thus for the formation of crystalline intelligence sensu Cattell (1963). If this ability is impaired, the development of crystalline abilities must therefore be expected to be impaired.

When evaluating the mixed findings on the association of media multitasking and interindividual differences in cognitive control and executive functions, it is important to consider the possibility that the inconsistency of findings may—at least partly—also be due to a lack of reliability of some studies, which may result from small samples and poor reliability of measures of individual differences in executive functions. In some of the studies described, individual differences in cognitive functions were assessed using experimental paradigms that differentiate more reliably between experimental conditions than between individuals with different abilities (Enkavi et al., 2018; Hedge et al., 2018; Paap & Sawi, 2016). In the field of research on correlates of media multitasking, the problem of poor reliability, documented especially for measures based on reaction time differences, has been considered in few studies (e.g., Alzahabi et al., 2017). In order to understand inconsistent findings in the field and avoid conclusions based on unreliable measures, it would be important to consistently report the reliability of executive function measures in studies for this research field and ensure the use of reliable measures.

Another important limitation of the validity of almost all existing studies on the relationship between media multitasking and cognitive performance lies in their purely correlational nature. All studies from this field described above examine correlates of the extent of media multitasking reported by study participants by self-report in cross-sectional research designs. The resulting data do not allow us to draw conclusions about the causes of the observed associations. We do not know whether media multitasking leads to poorer attentional control or—conversely—whether a lower ability to maintain focused attention favors media multitasking. Furthermore, it is conceivable that preexisting differences in third variables influence both attentional functions and the extent and pattern of media use. To better understand the underlying causal relationships, we need longitudinal studies and, ideally, experimental interventions. In one longitudinal study, media multitasking was associated with a slightly increased likelihood of developing symptoms of attention-deficit/hyperactivity disorder (ADHD). Of 2587 adolescents aged 15–16 years who, according to self-report questionnaires, had no significant ADHD symptoms at baseline, those who had used the most digital media in the interim showed a slightly higher rate of ADHD symptoms after 2 years (Ra et al., 2018). While this study suggests that media use may indeed have an impact on the longer-term development of attentional functions, a causal relationship can only be demonstrated by experimental studies, which, however, do not yet exist on the topic of media multitasking.

An obvious candidate for a trait with preexisting differences that could explain differences in attentional control/executive functioning as well as media use is *intelligence*. Studies independent of the topic of media multitasking have shown that individual differences in intelligence are related to differences in attentional control and executive functions (Chen et al., 2019; Ren et al., 2013; Schweizer et al., 2005). In this regard, some studies suggest a close relationship between attentional control and intelligence, which may mediate the also well-documented link between intelligence and working memory capacity (Burgess et al., 2011; Conway et al., 2003; Engle et al., 1999; Unsworth, 2014). Furthermore, intelligence has also been linked to the distinction between relevant and irrelevant information in cognitive information processing (Hilger et al., 2017; Melnick et al., 2013).

While most studies on media multitasking have not collected a separate measure of intelligence in addition to measures of attentional control and executive functions, one study that is an exception in this regard showed a negative relation between intelligence and media multitasking. In a student sample, participants who self-reported more media multitasking performed worse on a test of fluid intelligence (Raven's matrices) than participants who engaged in less media multitasking (Minear et al., 2013). It is conceivable, then, that preexisting differences in intelligence mediate the relationship between media multitasking and cognitive ability. Intelligence differences could thereby also underlie the lower neural efficiency reported for media multitaskers. Lower neural efficiency has also been associated with lower intelligence. In some studies, participants with lower intelligence scores—similar to the study on media multitasking by Moisala et al. (2016)—showed greater activation in frontal brain regions during cognitive load (Basten et al., 2015).

In addition to differences in intelligence, differences in personality traits also seem to play a role in the individual tendency to engage in media multitasking. According to self-report in questionnaires, media multitasking correlates positively with impulsivity and sensation seeking (Jeong & Fishbein, 2007; König et al., 2010; Minear et al., 2013; Sanbonmatsu et al., 2013) and negatively with self-control and reward deferral (Minear et al., 2013; Schutten et al., 2017). If—depending on personality and intelligence—stable individual differences in strategies and abilities for cognitive control exist, then it is to be expected that some individuals have difficulties in dealing with a broader range of media offers due to their individual predisposition, that they are less able to resist the broad range of options due to weaker attentional and self-control, and that they are thus more susceptible to media multitasking.

4 Influence of Addictive Gaming on Cognitive Development

Excessive gaming also increases the risk of developing a gaming disorder, which is characterized by addictive use of video games. Children and adolescents with gaming disorder show poorer school performance (Brunborg et al., 2014; Gentile et al., 2011; Haghbin et al., 2013; Rehbein et al., 2010, 2015; Stavropoulos et al., 2013; Strittmatter et al., 2015) and higher school absenteeism (Austin & Totaro, 2011). Many studies show an association between higher prevalence of problematic and addictive media use and lower academic levels (Elliott et al., 2012; Rehbein et al., 2015; Thomasius, 2020), as well as an association between lower parental school completion and higher prevalence of problematic and addictive use (Thomasius, 2020). In populations of individuals with gaming disorder, the rate of unemployment is significantly higher compared to the national average (Lindenberg et al., 2017).

The fact that excessive media use, especially playing computer games (*gaming*), can also be addictive has been officially recognized by the World Health Organization through the introduction of the new category "addictive behavior disorders" in ICD-11 (World Health Organization, 2018). Affected individuals exhibit excessive levels of video game use that cause significant distress, and an increasingly strong desire (*craving*) for gaming. Individuals with intense use of high-reinforcement video games show more activation in the reward system during gaming (Dong et al., 2017). Etiologically, this is explained by a sensitization of the reward system to gaming-associated stimuli. The prevalence of gaming disorder and Internet addiction increases from 3 to 9% between puberty and late adolescence (Lindenberg et al., 2018). Impaired decision-making processes (Yao et al., 2014, 2015) and impairments in attentional control (van Holst et al., 2012) and cognitive control (Luijten et al., 2015) appear to play a major role in the development and maintenance of addicted video game use. Affected individuals lose control over the onset and completion, frequency, duration, and setting of use.Thus, gaming is increasingly prioritized over other everyday tasks, at the expense of acquiring crystalline skills or otherwise rewarding activities (e.g., schooling, other leisure activities, relationships, family). Negative consequences are minimized or denied and gaming is continued despite negative consequences such as school failure, loss of relationships or family conflicts. For an overview of gaming disorder and Internet addiction in adolescence, see Lindenberg et al. (2020).

The fact that video games are so attractive to children and adolescents is explained by immediate strong reward mechanisms that are consciously anchored in the development of these games. Processes of positive reinforcement, negative reinforcement, and intermittent reinforcement play a crucial role. Direct positive reinforcing factors in gaming include simply achievable, immediate feelings of success and a pleasant flow experience (Wölfling et al., 2013). Based on the laws of operant learning (Skinner, 1937), it can be explained that positive reinforcing consequences in principle lead to an increased frequency and intensity of behavior. Individual responsiveness to positive reinforcement from video games depends on individual reward sensitivity and the availability of alternative rewarding elements in everyday life. The tendency to be seduced by feelings of achievement and the pleasurable flow experience, and to invest increasing amounts of time in video games, is influenced by biopsychosocial factors. Genetic factors and neurobiological conditions, personality traits (high habitual anxiety, social inhibition, boredom susceptibility, low conscientiousness, lower achievement orientation), and sociocultural factors (family situation, stresses, conflicts, resources; Brand et al., 2019; Wölfling et al., 2013) are discussed.

As with substance-related disorders, the dependence-producing effects of the video game play a major role in game disorder, i.e., the specific reinforcing characteristics of the video game, which differ according to genre and game. Commercial video games purposefully contain diverse mechanisms placed by game developers to maximize individual play time. Most economic concepts of game producers include the offer of so-called "free-to-play" games, which are initially offered for free. Via the non-existent purchase price, the threshold is lowered to try out a game, which they quickly enjoy due to the intensive reinforcement mechanisms at the beginning of a video game. The already high game duration and the associated investment in the game are intended to increase the willingness to pay for the game ("pay-to-win") in the following course through microtransactions ("in-app purchases"), in the expectation of maintaining the initial reinforcement effect. This successful "foot-in-the-door" strategy of game producers is economically very successful and has the side effect that, due to the lack of an initial purchase price, the legal protection of minors does not apply (Illy & Florack, 2018).

Intermittent reinforcement mechanisms and gambling facets are used to specifically induce dependence and increase the duration of playing time. According to operant conditioning laws, intermittent reinforcement is considered particularly resistant to extinction. A typical mechanism that involves intermittent reinforcement and is thus considered to be particularly addiction-producing is a nonlinear difficulty progression. While quick successes can be achieved at the beginning of a game, which is usually acquired for free, and habitual play is thus operant-conditioned, the difficulty level increases abruptly after a certain point. Users then have the opportunity to acquire bonuses or game-mechanical advantages through microtransactions in order to accelerate the declining game progress again and successfully continue their "project," in which they have already invested a lot of time and which thus has a high emotional value for them.

This seemingly irrational behavior of spending money and investing even more time in the game despite the lack of a sense of achievement can be explained by two social psychological phenomena. First, people tend to attribute a higher value to an outcome that they had to work hard to achieve than the objective value of the outcome. This phenomenon of *justification of effort* can be traced back to Leon Festinger's theory of cognitive dissonance (Festinger, 1957, 2001). Justification of effort is used as a theoretical explanation of why users attribute increasingly higher emotional valence to a game in order to justify the meaningfulness of their previous investments of time and money. Second, the more people have invested in a project, such as the time they have spent playing the video game or the bonuses they have already purchased, the more inclined they are to make further investments. The irreversible costs (*sunk costs*) influence the decision about future investments and lead to "good money being thrown after bad." This behavior, irrational from a decision-theoretical point of view, of continuing with an undertaking when an investment in the form of money, effort, or time has already been made, is referred to in social psychology as the *sunk-cost fallacy (*Kahneman & Tversky, 1979).

In addition, many games contain incentives that are packaged in gambling-like environments and are thus intermittently reinforcing. In many video games, there are virtual lotteries that contain a random collection of different items in virtual containers (*loot boxes*). These can be unlocked in the game. Loot boxes are often initially offered for free or are easy to find. As the game progresses, they must be purchased through microtransactions. They often only contain *cosmetic items that* improve the appearance of an avatar.

However, this also increases the emotional significance and perceived *self-commitment* to continue the "project" successfully (*sunk-cost fallacy*). This, in turn, increases the willingness to spend a lot of time playing the game and to attribute a higher value to the game (*justification of effort*). As a rule, these gambling elements are programmed in such a way that at the beginning of the game the probability of winning attractive items is very high in order to ensnare the user. As the game progresses, the probability of an attractive win decreases, but intermittently, so that occasional "lucky hits" further reinforce the behavior. These built-in random mechanisms cause the behavior to be particularly resistant to deletion. This increases the likelihood of participating in further lotteries through further microtransactions or even intensive time investment in the video game. As a result of this ever-increasing time of use and continuous stimulation of the dopaminergic system, structural changes in the brain are detectable, which also alter the reward system (Kuss et al., 2018). An addiction memory develops in which reward sensitivity to corresponding addictive stimuli increases with each exposure (Dong et al., 2017).

At the same time, the prioritization of gaming over other activities and duties leads to negative consequences (such as school failure, abandonment of other hobbies, conflicts, social withdrawal), which are associated with aversive emotions. Reduced behavioral flexibility (narrowing of behavior through repetitive media consumption) is also associated with reduced flexibility in the use of coping strategies to regulate emotions. In turn, to cope with negative emotions, children and adolescents make very frequent use of video games. The loss of reinforcers in other areas of life is compensated for by intensive gaming, which corresponds to negative reinforcement in learning theory and increases behavioral tendencies. Adolescents report that they frequently use video games for emotion regulation: most often to combat boredom (89% of children and adolescents), followed by the desire to escape reality (38%), to relieve stress (35%), and to forget worries (Thomasius, 2020). As a result, as addiction progresses, these indirect reinforcement principles in particular (reinforcement by omission of a negative consequence) increase, with gaming being used as a compensatory strategy to reduce aversive emotional states (anxiety, sadness, boredom). The initial direct reinforcement principles (gaming as a gratification strategy to induce positive emotional states) decrease. This lack of flexibility in affect regulation and the reported interactions are consistent with findings on neural correlates of addictive disorders (Kuss et al., 2018).

In addition to individual differences in reward sensitivity, which is increased by frequent video game use, decreased cognitive control appears to be a major factor in the development of addictive video game use. Decreased cognitive control is associated with both poorer academic and cognitive performance (Duckworth & Seligman, 2005; Mischel, Shoda, & Peake, 1988; Shoda, Mischel, & Peake, 1990) and more excessive media use (Blinka et al., 2015; Khang et al., 2013; Koo & Kwon, 2014). Students who cannot control their own gaming and internet behavior spend more time online and playing video games. This leads to a displacement of the precious resource of time that is lacking elsewhere, such as in academic contexts, which in turn leads to poorer academic and cognitive performance. Students with lower self-control have a greater tendency to put off unpleasant activities and chores (e.g., schoolwork). Procrastination has been repeatedly found to be a significant school-related risk factor for addictive media use (Anam-ul-Malik & Rafiq, 2016; Davis et al., 2002; Kim et al., 2017; Kindt et al., 2019; Thatcher et al., 2008).

Consistent with this, studies show that attention deficits (Carli et al., 2013; Wang et al., 2017) and decreased executive functions and increased impulsivity (Bargeron & Hormes, 2017) promote harmful media use. Although time spent online per se does not define addictive use, it increases the risk of developing an addiction (Durkee et al., 2012; Rumpf et al., 2014), both through exposure-dependent sensitization of the reward system (Wölfling et al., 2008) and through a relative reduction in the proportions of time that might alternatively favor intelligence development, particularly in the area of crystalline skill formation.

5 Interactions of Media Use and Intelligence

Are video games and digital media a curse or a blessing for intelligence development? On the one hand, studies on cognitive development show that video games can promote some cognitive functions that are closely related to fluid intelligence. This is particularly true for general processing speed and goal-directed attentional control. Spatial abilities, for which improvements have been reported in the context of video games, can also be understood as cognitive component functions of intelligence. On the other hand, studies of media multitasking raise the question of whether media use can also negatively affect attentional control, concentration, and learning success, and studies of computer game addiction link addicted use of video games to negative effects on cognitive development and academic achievement. It is a core criterion of video game disorder that video gaming takes precedence over other daily activities and responsibilities, as video games are so rewarding that other activities are neglected in favor of them. This leaves less time for the development of cognitive skills that are not directly addressed by the games and thus not trained during gaming. This applies in particular to the development of crystalline skills, i.e., the acquisition of knowledge (Weis & Cerankosky, 2010).

Conversely, however, one can also assume that as long as there is still enough time for the acquisition of crystalline knowledge, neither playing video games nor media multitasking will harm cognitive development. The "digital goldilocks hypothesis" (Przybylski & Weinstein, 2017) assumes an inverted U-shaped relationship between screen time and cognitive ability. It postulates that moderate use of 1–3 h a day can even have positive effects on cognitive development, for example, through the digital acquisition of knowledge or involvement in social networks.

Figure 9.1a illustrates brain systems for which changes in structure or function have been reported in association with digital media use. Shown in blue is a network associated with cognitive control (Dosenbach et al., 2008; Fox et al., 2005), represented here by the core regions of the dorsolateral prefrontal cortex (dlPFC), dorsal anterior cingulate cortex (dACC), and parietal cortex. Within this network, the dlPFC in particular is associated with goal-directed attentional control (Corbetta & Shulman, 2002).

The network plays an important role for intelligence. It is also known as the multiple demand (MD) system in the literature on the neural bases of intelligence

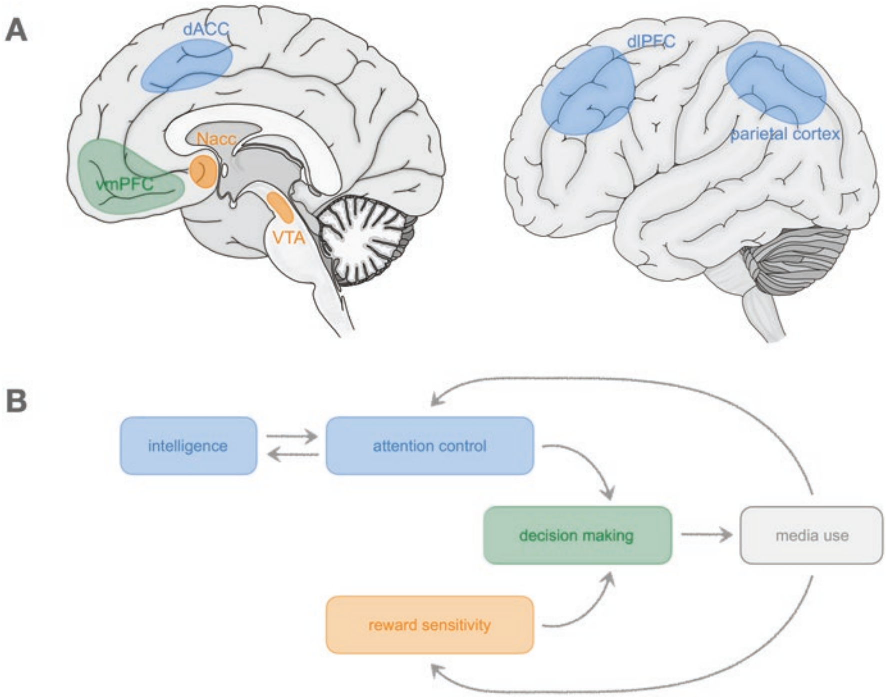

Fig. 9.1 Interactions of media use and intelligence. (**a**) Schematic representation of the brain regions that are relevant for the regulation and effects of media use. (**b**) Model of the mutual influence of intelligence and media use mediated by attentional control and reward sensitivity. See text for explanations. *dACC* dorsal anterior cingulate cortex, *dlPFC* dorsolateral prefrontal cortex, *Nacc* nucleus accumbens, *vmPFC* ventromedial prefrontal cortex, *VTA* area tegmentalis ventralis

(Duncan, 2010) and represents the core of the parieto-frontal integration theory (P-FIT) of intelligence (Jung & Haier, 2007).

Individual differences in intelligence have been linked to differences in the strength of activation in this network during cognitive challenges (Basten et al., 2015). In connection with the use of digital media, in particular the dlPFC should be highlighted from this network. As described above, the dlPFC showed an increase in gray matter in association with video game experience (Kühn et al., 2014), as well as a reduced neuronal efficiency in association with media multitasking (Moisala et al., 2016).

The regions of the brain highlighted in orange in Fig. 9.1a house two core structures of the mesolimbic reward system, the nucleus accumbens (Nacc) and the area tegmentalis ventralis (VTA). These brain regions respond with increased activity to reward stimuli—both unexpected rewards and learned stimuli that function as cues for reward (Schultz et al., 1998). The reward system is especially associated with the anticipation of rewards (Knutson et al., 2000) and thus represents a core structure for mediating craving (cf. Wanting vs. Liking; Berridge & Robinson, 2003), which plays an important role in explaining computer game addiction (Brand et al., 2019).

We assume that both the control network highlighted in blue in Fig. 9.1a and the reward system highlighted in orange play a significant role in controlling individual media use behavior. Above, it has already been explained in detail that various factors of computer games affect the reward system. It can be assumed that individuals with a high individual reward sensitivity show a stronger tendency to use computer games due to higher reinforcement from the reward stimuli associated with gaming. On the other hand, a higher individual capacity for attentional control allows for a more effective regulation of behavioral tendencies. In particular, the ventromedial prefrontal cortex (vmPFC, highlighted in green in Fig. 9.1a) is associated with decision making based on the integration of expected positive and negative behavioral consequences (Basten et al., 2015; Bechara et al., 2000; Young et al., 2010). This region might also be involved in individual decisions about media use behavior. Based on the findings on media use, cognitive abilities, and neural correlates described above, we propose the model outlined in Fig. 9.1b to conceptualize possible causal relationships. We assume that individual differences in attentional control and reward sensitivity mediated by a decision process that weighs expected positive against possible negative behavioral consequences are the crucial determinants of media use behavior. Grossly simplified, we hypothesize that high reward sensitivity and low attentional control represent risk factors for adverse media use behaviors that include unproductive media multitasking, excessive gaming and addictive video game use, and performance decrements due to neglect of other life domains (e.g., school, college, work). On the other hand, moderate reward sensitivity and a high ability to control attention represent protective factors that favor a controlled and goal-directed use of digital media.

According to this model, a particularly high risk of problematic media use would be expected for individuals that are characterized by a high reward sensitivity, while at the same time showing a low ability to control attention. It may further be assumed that a risk factor, such as an individually high reward sensitivity, can be balanced out by a protective factor, such as a simultaneously high level of attentional control. This example highlights the particular importance of strong attentional control for the responsible use of digital media, including video games. As explained above, this factor is closely related to intelligence (Schweizer et al., 2005). Thus, we assume that intelligence plays an important role for the individual pattern of media use and its consequences.

Figure 9.1b also indicates the feedback effect of media use on the factors that contribute to it. For video games in particular, a positive effect on attentional control is well documented (see above, *Influence of video games on cognitive development*). Such an improvement in attentional functions can—if we understand attentional control as a cognitive component function of intelligence—be interpreted as an indirect effect of media use on intelligence. In the field of media multitasking, on the other hand, the possibility of impairments in attentional control is discussed, which accordingly could be interpreted as a negative effect on intelligence (but see above, for a critique of the correlative approach of the relevant research). Media use also has an effect on individual reward sensitivity. Here, one generally assumes an increase in sensitivity to rewards by media use (see above, *Influence of addictive video game use on cognitive development*). These examples are meant to illustrate that positive and negative feedback loops can be mapped in the model, which can explain positive and negative effects on cognitive abilities and intelligence. In general, high intelligence and good attentional control will facilitate the controlled and goal-directed use of media that not only avoids negative effects but also includes positive "feedback loops" on attention and intelligence.

Bibliography

Alzahabi, R., & Becker, M. W. (2013). The association between media multitasking, task-switching, and dual-task performance. *Journal of Experimental Psychology: Human Perception and Performance, 39*(5), 1485–1495. https://doi.org/10.1037/a0031208

Alzahabi, R., Becker, M. W., & Hambrick, D. Z. (2017). Investigating the relationship between media multitasking and processes involved in task-switching. *Journal of Experimental Psychology: Human Perception and Performance, 43*(11), 1872–1894. https://doi.org/10.1037/xhp0000412

Anam-ul-Malik, & Rafiq, N. (2016). Exploring the relationship of personality, loneliness, and online social support with Interned addiction and procrastination. *Pakistan Journal of Psychological Research, 31*(1), 93–117.

Austin, W. A., & Totaro, M. W. (2011). Gender differences in the effects of Internet usage on high school absenteeism. *Journal of Socio-Economics, 40*(2), 192–198. https://doi.org/10.1016/j.socec.2010.12.017

Baniqued, P. L., Lee, H., Voss, M. W., Basak, C., Cosman, J. D., DeSouza, S., et al. (2013). Selling points: What cognitive abilities are tapped by casual video games? *Acta Psychologica, 142*(1), 74–86. https://doi.org/10.1016/j.actpsy.2012.11.009

Bargeron, A. H., & Hormes, J. M. (2017). Psychosocial correlates of internet gaming disorder: Psychopathology, life satisfaction, and impulsivity. *Computers in Human Behavior, 68*, 388–394. https://doi.org/10.1016/j.chb.2016.11.029

Basten, U., Hilger, K., & Fiebach, C. J. (2015). Where smart brains are different: A quantitative meta-analysis of functional and structural brain imaging studies on intelligence. *Intelligence, 51*, 10–27. https://doi.org/10.1016/j.intell.2015.04.009

Baumgartner, S. E., Weeda, W. D., van der Heijden, L. L., & Huizinga, M. (2014). The relationship between media multitasking and executive function in early adolescents. *Journal of Early Adolescence, 34*(8), 1120–1144. https://doi.org/10.1177/0272431614523133

Bavelier, D., & Green, C. S. (2019). Enhancing attentional control: Lessons from action video games. *Neuron, 104*(1), 147–163. https://doi.org/10.1016/j.neuron.2019.09.031

Bechara, A., Tranel, D., & Damasio, H. (2000). Characterization of the decision-making deficit of patients with ventromedial prefrontal cortex lesions. *Brain: A Journal of Neurology, 123*(Pt 11), 2189–2202. https://doi.org/10.1093/brain/123.11.2189

Bediou, B., Adams, D. M., Mayer, R. E., Tipton, E., Green, C. S., & Bavelier, D. (2018). Meta-analysis of action video game impact on perceptual, attentional, and cognitive skills. *Psychological Bulletin, 144*(1), 77–110. https://doi.org/10.1037/bul0000130

Bedwell, W. L., Pavlas, D., Heyne, K., Lazzara, E. H., & Salas, E. (2012). Toward a taxonomy linking game attributes to learning: An empirical study. *Simulation & Gaming, 43*(6), 729–760. https://doi.org/10.1177/1046878112439444

Berridge, K. C., & Robinson, T. E. (2003). *Parsing reward. Trends in Neurosciences, 26*(9), 507–513. https://doi.org/10.1016/S0166-2236(03)00233-9

Blacker, K. J., & Curby, K. M. (2013). Enhanced visual short-term memory in action video game players. *Attention, Perception, & Psychophysics, 75*(6), 1128–1136. https://doi.org/10.3758/s13414-013-0487-0

Blinka, L., Skarupova, K., Sevcikova, A., Wolfling, K., Muller, K. W., & Dreier, M. (2015). Excessive internet use in European adolescents: What determines differences in severity? *International Journal of Public Health, 60*(2), 249–256. https://doi.org/10.1007/s00038-014-0635-x

Bowman, L. L., Levine, L. E., Waite, B. M., & Gendron, M. (2010). Can students really multitask? An experimental study of instant messaging while reading. *Computers & Education, 54*(4), 927–931. https://doi.org/10.1016/j.compedu.2009.09.024

Burgess, G. C., Gray, J. R., Conway, A. R. A., & Braver, T. S. (2011). Neural mechanisms of interference control underlie the relationship between fluid intelligence and working memory span. *Journal of Experimental Psychology: General, 140*(4), 674–692. https://doi.org/10.1037/a0024695

Brand, M., Wegmann, E., Stark, R., Müller, A., Wölfling, K., Robbins, T. W., & Potenza, M. N. (2019). The Interaction of Person-Affect-Cognition-Execution (I-PACE) model for addictive behaviors: Update, generalization to addictive behaviors beyond internet-use disorders, and specification of the process character of addictive behaviors. *Neuroscience and Biobehavioral Reviews, 104*, 1–10. https://doi.org/10.1016/j.neubiorev.2019.06.032

Brunborg, G. S., Mentzoni, R. A., & Frøyland, L. R. (2014). Is video gaming, or video game addiction, associated with depression, academic achievement, heavy episodic drinking, or conduct problems? *Journal of Behavioral Addictions, 3*(1), 27–32. https://doi.org/10.1556/JBA.3.2014.002

Cain, M. S., & Mitroff, S. R. (2011). Distractor filtering in media multitaskers. *Perception, 40*(10), 1183–1192. https://doi.org/10.1068/p7017

Carli, V., Durkee, T., Wasserman, D., Hadlaczky, G., Despalins, R., Kramarz, E., et al. (2013). The association between pathological internet use and comorbid psychopathology: A systematic review. *Psychopathology, 46*(1), 1–13. https://doi.org/10.1159/000337971

Carrier, L. M., Rosen, L. D., Cheever, N. A., & Lim, A. F. (2015). Causes, effects, and practicalities of everyday multitasking. *Developmental Review, 35*, 64–78. https://doi.org/10.1016/j.dr.2014.12.005

Cattell, R. B. (1963). Theory of fluid and crystallized intelligence: A critical experiment. *Journal of Educational Psychology, 54*(1), 1–22. https://doi.org/10.1037/h0046743

Chisholm, J. D., & Kingstone, A. (2012). Improved top-down control reduces oculomotor capture: The case of action video game players. *Attention, Perception, & Psychophysics, 74*(2), 257–262. https://doi.org/10.3758/s13414-011-0253-0

Chisholm, J. D., & Kingstone, A. (2015). Action video games and improved attentional control: Disentangling selection- and response-based processes. *Psychonomic Bulletin & Review, 22*(5), 1430–1436. https://doi.org/10.3758/s13423-015-0818-3

Chisholm, J. D., Hickey, C., Theeuwes, J., & Kingstone, A. (2010). Reduced attentional capture in action video game players. *Attention, Perception, & Psychophysics, 72*(3), 667–671. https://doi.org/10.3758/APP.72.3.667

Chen, Y., Spagna, A., Wu, T., Kim, T. H., Wu, Q., Chen, C., Wu, Y., & Fan, J. (2019). Testing a Cognitive Control Model of Human Intelligence. *Scientific Reports, 9*(1), 2898. https://doi.org/10.1038/s41598-019-39685-2

Conway, A. R. A., Kane, M. J., & Engle, R. W. (2003). Working memory capacity and its relation to general intelligence. *Trends in Cognitive Sciences, 7*(12), 547–552. https://doi.org/10.1016/j.tics.2003.10.005

Corbetta, M., & Shulman, G. L. (2002). Control of goal-directed and stimulus-driven attention in the brain. *Nature Reviews. Neuroscience, 3*(3), 201–215. https://doi.org/10.1038/nrn755

Dale, G., & Green, C. S. (2017). The changing face ofvideo games and video gamers: Future directions in the scientific study of video game play and cognitive performance. *Journal of Cognitive Enhancement, 1*(3), 280–294. https://doi.org/10.1007/s41465017-0015-6

Davis, R. A., Flett, G. L., & Besser, A. (2002). Validation of a new scale for measuring problematic Internet use: Implications for pre-employment screening. *CyberPsychology & Behavior, 5*(4), 331–345. https://doi.org/10.1089/109493102760275581

Dong, G., Wang, L., Du, X., & Potenza, M. N. (2017). Gaming increases craving to gaming-related stimuli in individuals with internet gaming disorder. *Biological Psychiatry. Cognitive Neuroscience and Neuroimaging, 2*(5), 404–412. https://doi.org/10.1016/j.bpsc.2017.01.002

Dosenbach, N. U. F., Fair, D. A., Cohen, A. L., Schlaggar, B. L., & Petersen, S. E. (2008). A dual-networks architecture of top-down control. *Trends in Cognitive Sciences, 12*(3), 99–105. https://doi.org/10.1016/j.tics.2008.01.001

Duckworth, A. L. & Seligman, M. E. P. (2005). Self-discipline outdoes IQ in predicting academic performance of adolescents. *Psychological Science, 16*(12), 939–944. https://doi.org/10.1111/j.1467-9280.2005.01641.x

Duncan, J. (2010). The multiple-demand (MD) system of the primate brain: Mental programs for intelligent behavior. *Trends in Cognitive Sciences, 14*(4), 172–179. https://doi.org/10.1016/j.tics.2010.01.004

Durkee, T., Kaess, M., Carli, V., Parzer, P., Wasserman, C., Floderus, B., et al. (2012). Prevalence of pathological internet use among adolescents in Europe: Demographic and social factors. *Addiction, 107*(12), 2210–2222. https://doi.org/10.1111/j.1360-0443.2012.03946.x

Dye, M. W. G., Green, C. S., & Bavelier, D. (2009). Increasing speed of processing with action video games. *Current Directions in Psychological Science, 18*(6), 321–326. https://doi.org/10.1111/j.1467-8721.2009.01660.x

Elbe, P., Sörman, D. E., Mellqvist, E., Brändström, J., & Ljungberg, J. K. (2019). Predicting attention shifting abilities from self-reported media multitasking. *Psychonomic Bulletin & Review, 26*(4), 1257–1265. https://doi.org/10.3758/s13423-018-01566-6

Elliott, L., Ream, G., McGinsky, E., & Dunlap, E. (2012). The contribution of game genre and other use patterns to problem video game play among adult video gamers. *International Journal of Mental Health and Addiction, 10*(6), 948–969. https://doi.org/10.1007/s11469-012-9391-4

Enkavi, A. Z., Eisenberg, I. W., Bissett, P., Mazza, G. L., MacKinnon, D., Marsch, L., & Poldrack, R. (2018). Large-scale analysis of test–retest reliabilities of self-regulation measures. *PNAS 116*(12), 5472–5477. https://www.pnas.org/doi/epdf/10.1073/pnas.1818430116

Engle, R. W., Tuholski, S. W., Laughlin, J. E., & Conway, A. R. A. (1999). Working memory, short-term memory, and general fluid intelligence: A latent-variable approach. *Journal of Experimental Psychology. General, 128*(3), 309–331. https://doi.org/10.1037/0096-3445.128.3.309

Faisal, A., & Peltoniemi, M. (2018). Establishing video game genres using data-driven modeling and product databases. *Games and Culture, 13*(1), 20–43. https://doi.org/10.1177/1555412015601541

Feng, J., Spence, I., & Pratt, J. (2007). Playing an action video game reduces gender dfferences in spatial cognition. *Psychological Science, 18*(10), 850–855. https://doi.org/10.1111/j.1467-9280.2007.01990.x

Festinger, L. (1957). *A theory of cognitive dissonance*. Stanford University Press.

Festinger, L. (2001). *A theory of cognitive dissonance* (Reissued by Stanford University Press in 1962, renewed 1985 by author [Reprint]). Stanford University Press.

Foerde, K., Knowlton, B. J., & Poldrack, R. A. (2006). Modulation of competing memory systems by distraction. *Proceedings of the National Academy of Sciences, 103*(31), 11778–11783. https://doi.org/10.1073/pnas.0602659103

Fox, M. D., Snyder, A. Z., Vincent, J. L., Corbetta, M., van Essen, D. C., & Raichle, M. E. (2005). The human brain is intrinsically organized into dynamic, anticorrelated functional networks. *Proceedings of the National Academy of Sciences, 102*(27), 9673–9678. https://doi.org/10.1073/pnas.0504136102

Gentile, D. A., Choo, H., Liau, A., Sim, T., Li, D., Fung, D., & Khoo, A. (2011). Pathological video game use among adolescents: A two-year longitudinal study. *Pediatrics, 127*(2), e319–e329. https://doi.org/10.1542/peds.2010-1353

Green, C. S., & Bavelier, D. (2003). Action video game modifies visual selective attention. *Nature, 423*(6939), 534–537. https://doi.org/10.1038/nature01647

Green, C. S., Pouget, A., & Bavelier, D. (2010). Improved probabilistic inference as a general learning mechanism with action video games. *Current Biology, 20*(17), 1573–1579. https://doi.org/10.1016/j.cub.2010.07.040

Haghbin, M., Shaterian, F., Hosseinzadeh, D., & Griffiths, M. D. (2013). A brief report on the relationship between self-control, video game addiction and academic achievement in normal and ADHD students. *Journal of Behavioral Addictions, 2*(4), 239–243. https://doi.org/10.1556/JBA.2.2013.4.7

Hedge, C., Powell, G., & Sumner, P. (2018). The reliability paradox: Why robust cognitive tasks do not produce reliable individual differences. *Behavior Research Methods, 50*(3), 1166–1186. https://doi.org/10.3758/s13428-017-0935-1

Hilger, K., Ekman, M., Fiebach, C. J., & Basten, U. (2017). Efficient hubs in the intelligent brain: Nodal efficiency of hub regions in the salience network is associated with general intelligence. *Intelligence, 60*, 10–25. https://doi.org/10.1016/j.intell.2016.11.001

Illy, D., & Florack, J. (2018). *Video game and internet addiction guidebook: Help for everyday life. German Medical Collection* (Vol. 93). Elsevier. Retrieved from http://www.sciencedirect.com/science/book/9783437229916

Jacobsen, W. C., & Forste, R. (2011). The wired generation: Academic and social outcomes of electronic media use among university students. *Cyberpsychology, Behavior and Social Networking, 14*(5), 275–280. https://doi.org/10.1089/cyber.2010.0135

Jeong, S.-H., & Fishbein, M. (2007). Predictors of Multitasking with Media: Media Factors and Audience Factors. *Media Psychology, 10*(3), 364–384. https://doi.org/10.1080/15213260701532948

Junco, R., & Cotten, S. R. (2011). Perceived academic effects of instant messaging use. *Computers & Education, 56*(2), 370–378. https://doi.org/10.1016/j.compedu.2010.08.020

Jung, R. E., & Haier, R. J. (2007). The parieto-frontal integration theory (P-FIT) of intelligence: Converging neuroimaging evidence. *Behavioral and Brain Sciences, 30*(2), 135–154; discussion 154–187. https://doi.org/10.1017/S0140525X07001185

Kahneman, D., & Tversky, A. (1979). Prospect theory: An analysis of decision under risk. *Econometrica, 74*(2), 263–291.

Khang, H., Kim, J. K., & Kim, Y. (2013). Self-traits and motivations as antecedents of digital media flow and addiction: The Internet, mobile phones, and video games. *Computers in Human Behavior, 29*(6), 2416–2424. https://doi.org/10.1016/j.chb.2013.05.027

Kilgard, M. P., & Merzenich, M. M. (1998). Cortical map reorganization enabled by nucleus basalis activity. *Science, 279*(5357), 1714–1718. https://doi.org/10.1126/science.279.5357.1714

Kim, J., Hong, H., Lee, J., & Hyun, M.-H. (2017). Effects of time perspective and selfcontrol on procrastination and Internet addiction. *Journal of Behavioral Addictions, 6*(2), 229–236. https://doi.org/10.1556/2006.6.2017.017

Kindt, S., Szász-Janocha, C., Rehbein, F., & Lindenberg, K. (2019). School-related risk factors of internet use disorders. *International Journal of Environmental Research and Public Health, 16*(24), 4938. https://doi.org/10.3390/ijerph16244938

Knutson, B., Westdorp, A., Kaiser, E., & Hommer, D. (2000). Fmri visualization of brain activity during a monetary incentive delay task. *NeuroImage, 12*(1), 20–27. https://doi.org/10.1006/nimg.2000.0593

Koo, H. J., & Kwon, J.-H. (2014). Risk and protective factors of internet addiction: A metaanalysis of empirical studies in Korea. *Yonsei Medical Journal, 55*(6), 1691–1711. https://doi.org/10.3349/ymj.2014.55.6.1691

König, C. J., Oberacher, L., & Kleinmann, M. (2010). Personal and Situational Determinants of Multitasking at Work. *Journal of Personnel Psychology, 9*(2), 99–103. https://doi.org/10.1027/1866-5888/a000008

Krishnan, L., Kang, A., Sperling, G., & Srinivasan, R. (2013). Neural strategies for selective attention distinguish fast-action video game players. *Brain Topography, 26*(1), 83–97. https://doi.org/10.1007/s10548-012-0232-3

Kühn, S., Gleich, T., Lorenz, R. C., Lindenberger, U., & Gallinat, J. (2014). Playing Super Mario induces structural brain plasticity: Gray matter changes resulting from training with a commercial video game. *Molecular Psychiatry, 19*(2), 265–271. https://doi.org/10.1038/mp.2013.120

Kühn, S., Romanowski, A., Schilling, C., Lorenz, R., Mörsen, C., Seiferth, N., et al. (2011). The neural basis of video gaming. *Translational Psychiatry, 1*(11), e53–e53.

Kuss, D. J., Pontes, H. M., & Griffiths, M. D. (2018). Neurobiological correlates in internet gaming disorder: A systematic literature review. *Frontiers in Psychiatry, 9*, 166. https://doi.org/10.3389/fpsyt.2018.00166

Lindenberg, K., Halasy, K., Szász-Janocha, C., & Wartberg, L. (2018). A phenotype classification of Internet Use Disorder in a large-scale high-school study. *International Journal of Environmental Research and Public Health, 15*(4), 733. https://doi.org/10.3390/ijerph15040733

Lindenberg, K., Kindt, S., & Szász-Janocha, C. (2020). *Internet addiction in adolescents: The PROTECT program for evidence-based prevention and treatment*. Springer.

Lindenberg, K., Szász-Janocha, C., Schoenmaekers, S., Wehrmann, U., & Vonderlin, E. (2017). An analysis of integrated health care for Internet Use Disorders in adolescents and adults. *Journal of Behavioral Addictions, 6*(4), 579–592. https://doi.org/10.1556/2006.6.2017.065

Lorenz, R. C., Gleich, T., Gallinat, J., & Kühn, S. (2015). Video game training and the reward system. *Frontiers in Human Neuroscience, 9*, 40. https://doi.org/10.3389/fnhum.2015.00040

Luijten, M., Meerkerk, G.-J., Franken, I. H. A., van de Wetering, B. J. M., & Schoenmakers, T. M. (2015). An fMRI study of cognitive control in problem gamers. *Psychiatry Research, 231*(3), 262–268. https://doi.org/10.1016/j.pscychresns.2015.01.004

Mack, D. J., & Ilg, U. J. (2014). The effects of video game play on the characteristics of saccadic eye movements. *Vision Research, 102*, 26–32. https://doi.org/10.1016/j.visres.2014.07.010

Madore, K. P., Khazenzon, A. M., Backes, C. W., Jiang, J., Uncapher, M. R., Norcia, A. M., & Wagner, A. D. (2020). Memory failure predicted by attention lapsing and media multitasking. *Nature, 587*(7832), 87–91. https://doi.org/10.1038/s41586020-2870-z

Medienpädagogischer Forschungsverbund Südwest. (2018). *KIMStudy 2018: Childhood, Internet, media. Baseline study on media use among 6- to 13-year-olds*. Retrieved from https://www.mpfs.de/fileadmin/files/Studien/KIM/2018/KIMStudie_2018_web.pdf

Medienpädagogischer Forschungsverbund Südwest. (2020). *JIM-study 2020: Youth, information, media*. Retrieved from https://www.mpfs.de/fileadmin/files/Studien/JIM/2020/JIM-Study-2020_Web_final.pdf

Melnick, M. D., Harrison, B. R., Park, S., Bennetto, L., & Tadin, D. (2013). A strong interactive link between sensory discriminations and intelligence. *Current Biology, 23*(11), 1013–1017. https://doi.org/10.1016/j.cub.2013.04.053

Minear, M., Brasher, F., McCurdy, M., Lewis, J., & Younggren, A. (2013). Working memory, fluid intelligence, and impulsiveness in heavy media multitaskers. *Psychonomic Bulletin & Review, 20*(6), 1274–1281. https://doi.org/10.3758/s13423-013-0456-6

Mischel, W., Shoda, Y. & Peake, P. K. (1988). The nature of adolescent competencies predicted by preschool delay of gratification. *Journal of Personality and Social Psychology, 54*(4), 687–696.

Mishra, J., Zinni, M., Bavelier, D., & Hillyard, S. A. (2011). Neural basis of superior performance of action videogame players in an attention-demanding task. *Journal of Neuroscience, 31*(3), 992–998. https://doi.org/10.1523/JNEUROSCI.483410.2011

Moisala, M., Salmela, V., Hietajärvi, L., Salo, E., Carlson, S., Salonen, O., et al. (2016). Media multitasking is associated with distractibility and increased prefrontal activity in adolescents and young adults. *NeuroImage, 134*, 113–121. https://doi.org/10.1016/j.neuroimage.2016.04.011

Okagaki, L., & Frensch, P. A. (1994). Effects of video game playing on measures of spatial performance: Gender effects in late adolescence. *Journal of Applied Developmental Psychology, 15*(1), 33–58. https://doi.org/10.1016/0193-3973(94)90005-1

Ophir, E., Nass, C., & Wagner, A. D. (2009). Cognitive control in media multitaskers. *Proceedings of the National Academy of Sciences, 106*(37), 15583–15587. https://doi.org/10.1073/pnas.0903620106

Paap, K. R., & Sawi, O. (2016). The role of test-retest reliability in measuring individual and group differences in executive functioning. *Journal of Neuroscience Methods, 274*, 81–93. https://doi.org/10.1016/j.jneumeth.2016.10.002

Palaus, M., Marron, E. M., Viejo-Sobera, R., & Redolar-Ripoll, D. (2017). Neural basis of video gaming: A systematic review. *Frontiers in Human Neuroscience, 11*, 248. https://doi.org/10.3389/fnhum.2017.00248

Poldrack, R. A., & Foerde, K. (2008). Category learning and the memory systems debate. *Neuroscience & Biobehavioral Reviews, 32*(2), 197–205. https://doi.org/10.1016/j.neubiorev.2007.07.007

Przybylski, A. K., & Weinstein, N. (2017). A large-scale test of the goldilocks hypothesis: Quantifying the relations between dgital-screen use and the mental well-being of adolescents. *Psychological Science, 28*(2), 204–215. https://doi.org/10.1177/0956797616678438

Ra, C. K., Cho, J., Stone, M. D., de La Cerda, J., Goldenson, N. I., Moroney, E., et al. (2018). Association of digital media use with subsequent symptoms of attention-deficit/hyperactivity disorder among adolescents. *JAMA, 320*(3), 255. https://doi.org/10.1001/jama.2018.8931

Ralph, B. C. W., Thomson, D. R., Cheyne, J. A., & Smilek, D. (2014). Media multitasking and failures of attention in everyday life. *Psychological Research, 78*(5), 661–669. https://doi.org/10.1007/s00426-013-0523-7

Ralph, B. C. W., Thomson, D. R., Seli, P., Carriere, J. S. A., & Smilek, D. (2015). Media multitasking and behavioral measures of sustained attention. *Attention, Perception, & Psychophysics, 77*(2), 390–401. https://doi.org/10.3758/s13414-014-0771-7

Rehbein, F., Kleimann, M., & Mößle, T. (2010). Prevalence and risk factors of video game dependency in adolescence: Results of a German nationwide survey. *Cyberpsychology, Behavior and Social Networking, 13*(3), 269–277.

Rehbein, F., Kliem, S., Baier, D., Mößle, T., & Petry, N. M. (2015). Prevalence of Internet gaming disorder in German adolescents: Diagnostic contribution of the nine DSM-5 criteria in a statewide representative sample. *Addiction, 110*(5), 842–851. https://doi.org/10.1111/add.12849

Ren, X., Altmeyer, M., Reiss, S., & Schweizer, K. (2013). Processbased account for the effects of perceptual attention and executive attention on fluid intelligence: An integrative approach. *Acta Psychologica, 142*(2), 195–202. https://doi.org/10.1016/j.actpsy.2012.12.007

Rosen, L. D., Mark Carrier, L., & Cheever, N. A. (2013). Facebook and texting made me do it: Media-induced task-switching while studying. *Computers in Human Behavior, 29*(3), 948–958. https://doi.org/10.1016/j.chb.2012.12.001

Rumpf, H.-J., Vermulst, A. A., Bischof, A., Kastirke, N., Gürtler, D., Bischof, G., et al. (2014). Occurrence of internet addiction in a general population sample: A latent class analysis. *European Addiction Research, 20*(4), 159–166. https://doi.org/10.1159/000354321

Sanbonmatsu, D. M., Strayer, D. L., Medeiros-Ward, N., & Watson, J. M. (2013). Who Multi-Tasks and Why? Multi-Tasking Ability, Perceived Multi-Tasking Ability, Impulsivity, and Sensation Seeking. PLoS ONE, 8(1), e54402. https://doi.org/10.1371/journal.pone.0054402

Schultz, W., Tremblay, L., & Hollerman, J. R. (1998). Reward prediction in primate basal ganglia and frontal cortex. *Neuropharmacology, 37*(4–5), 421–429. https://doi.org/10.1016/S0028-3908(98)00071-9

Schutten, D., Stokes, K. A., & Arnell, K. M. (2017). I want to media multitask and I want to do it now: Individual differences in media multitasking predict delay of gratification and system-1 thinking. *Cognitive Research: Principles and Implications, 2*(1), 8. https://doi.org/10.1186/s41235-016-0048-x

Schweizer, K., Moosbrugger, H., & Goldhammer, F. (2005). The structure of the relationship between attention and intelligence. *Intelligence, 33*(6), 589–611. https://doi.org/10.1016/j.intell.2005.07.001

Shawn Green, C., Sugarman, M. A., Medford, K., Klobusicky, E., & Bavelier, D. (2012). The effect of action video game experience on task-switching. *Computers in Human Behavior, 28*(3), 984–994. https://doi.org/10.1016/j.chb.2011.12.020

Shoda, Y., Mischel, W. & Peake, P. K. (1990). Predicting adolescent cognitive and self-regulatory competencies from preschool delay of gratification. Identifying diagnostic conditions. Developmental Psychology, 26(6), 978–986. https://doi.org/10.1037/0012-1649.26.6.978

Skinner, B. F. (1937). *The behavior of organisms: An experimental analysis. The Century Psychology Series*. Appleton-Century Company.

Spence, I., Yu, J. J., Feng, J., & Marshman, J. (2009). Women match men when learning a spatial skill. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 35*(4), 1097–1103. https://doi.org/10.1037/a0015641

Stavropoulos, V., Alexandraki, K., & Motti-Stefanidi, F. (2013). Recognizing internet addiction: Prevalence and relationship to academic achievement in adolescents enrolled in urban and rural Greek high schools. *Journal of Adolescence, 36*(3), 565–576. https://doi.org/10.1016/j.adolescence.2013.03.008

Strittmatter, E., Kaess, M., Parzer, P., Fischer, G., Carli, V., Hoven, C. W., et al. (2015). Pathological Internet use among adolescents: Comparing gamers and non-gamers. *Psychiatry Research, 228*(1), 128–135. https://doi.org/10.1016/j.psychres.2015.04.029

Thatcher, A., Wretschko, G., & Fridjhon, P. (2008). Online flow experiences, problematic internet use and internet procrastination. *Computers in Human Behavior, 24*(5), 2236–2254. https://doi.org/10.1016/j.chb.2007.10.008

Thomasius, R. (2020). *Media Addiction 2020 - Gaming and Social Media in Times of Corona: DAK longitudinal study: Survey of children, adolescents (12-17 Years) and their parents)*. Retrieved from https://www.dak.de/dak/bundesthemen/computerspielsucht-2296282.html#/

Uncapher, M. R., & Wagner, A. D. (2018). Minds and brains of media multitaskers: Current findings and future directions. *Proceedings of the National Academy of Sciences, 115*(40), 9889–9896. https://doi.org/10.1073/pnas.1611612115

Unsworth, N. (2014). Working memory and fluid intelligence: Capacity, attention control, and secondary memory retrieval. *Cognitive Psychology, 26*.

Van Holst, R. J., Lemmens, J. S., Valkenburg, P. M., Peter, J., Veltman, D. J., & Goudriaan, A. E. (2012). Attentional bias and disinhibition toward gaming cues are related to problem gaming in male adolescents. *Journal of Adolescent Health, 50*(6), 541–546. https://doi.org/10.1016/j.jadohealth.2011.07.006

Wang, B.-Q., Yao, N.-Q., Zhou, X., Liu, J., & Lv, Z.-T. (2017). The association between attention deficit/hyperactivity disorder and internet addiction: A systematic review and meta-analysis. *BMC Psychiatry, 17*(1), 260. https://doi.org/10.1186/s12888017-1408-x

Weis, R., & Cerankosky, B. C. (2010). Effects of video-game ownership on young boys' academic and behavioral functioning: A randomized controlled study. *Psychological Science, 21*(4), 463–470. https://doi.org/10.1177/0956797610362670

Wilmer, H. H., Sherman, L. E., & Chein, J. M. (2017). Smartphones and cognition: A review of research exploring the links between mobile technology habits and cognitive functioning. *Frontiers in Psychology, 8*, 605. https://doi.org/10.3389/fpsyg.2017.00605

Wilms, I. L., Petersen, A., & Vangkilde, S. (2013). Intensive video gaming improves encoding speed to visual short-term memory in young male adults. *Acta Psychologica, 142*(1), 108–118. https://doi.org/10.1016/j.actpsy.2012.11.003

Wiradhany, W., & Nieuwenstein, M. R. (2017). Cognitive control in media multitaskers: Two replication studies and a meta-analysis. *Attention, Perception, & Psychophysics, 79*(8), 2620–2641. https://doi.org/10.3758/s13414-017-1408-4

Wölfling, K., Flor, H., & Grüsser, S. M. (2008). Psychophysiological responses to drug-associated stimuli in chronic heavy cannabis use. *European Journal of Neuroscience, 27*(4), 976–983. https://doi.org/10.1111/j.1460-9568.2008.06051.x

Wölfling, K., Jo, C., Bengesser, I., Beutel, M. E., & Müller, K. W. (2013). *Computer game and internet addiction: A cognitive-behavioral treatment manual. Disorder-specific psychotherapy*. Kohlhammer.

Wood, E., Zivcakova, L., Gentile, P., Archer, K., de Pasquale, D., & Nosko, A. (2012). Examining the impact of off-task multi-tasking with technology on real-time classroom learning. *Computers & Education, 58*(1), 365–374. https://doi.org/10.1016/j.compedu.2011.08.029

World Health Organization. (2018). *ICD-11: International Classification of Diseases 11th revision*. Retrieved from https://icd.who.int/browse11/l-m/en

Yao, Y.-W., Chen, P.-R., Chen, C., Wang, L.-J., Zhang, J.-T., Xue, G., et al. (2014). Failure to utilize feedback causes decision-making deficits among excessive Internet gamers. *Psychiatry Research, 219*(3), 583–588. https://doi.org/10.1016/j.psychres.2014.06.033

Yao, Y.-W., Wang, L.-J., Yip, S. W., Chen, P.-R., Li, S., Xu, J., et al. (2015). Impaired decision-making under risk is associated with gaming-specific inhibition deficits among college students with Internet gaming disorder. *Psychiatry Research, 229*(1–2), 302–309. https://doi.org/10.1016/j.psychres.2015.07.004

Young, L., Bechara, A., Tranel, D., Damasio, H., Hauser, M., & Damasio, A. (2010). Damage to ventromedial prefrontal cortex impairs judgment of harmful intent. *Neuron, 65*(6), 845–851. https://doi.org/10.1016/j.neuron.2010.03.003

Katajun Lindenberg has been Professor of Child and Adolescent Psychotherapy at Goethe University Frankfurt since 2020, where she heads the training and university outpatient clinics for child and adolescent psychotherapy. After studying psychology at the Universities of Heidelberg and Exeter (UK), she worked at the Psychotherapy Research Unit of Heidelberg University Hospital and completed her doctorate at Heidelberg University on the topic of E-Mental-Health in the prevention of mental disorders. While she continued her clinical training as a child and adolescent psychotherapist in Heidelberg at the Institute for Family Therapy, the Clinic for Child and Adolescent Psychiatry and the Centre for Psychological Psychotherapy, she continued her scientific career as a postdoctoral researcher at the University of Heidelberg. In 2012, she was a founding member and scientific director of the integrated diagnosis, counselling and treatment network for computer game and internet addiction Rhein-Neckar-Kreis, Heidelberg and Mannheim, which networks 15 clinical institutions in the region. In 2013, she was appointed as assistant professor at the Heidelberg University of Education. The prevention and early intervention program PROTECT, which she developed there, is currently translated into four languages. In 2019, she received her license to practice as a child and adolescent psychotherapist. In the same year, she was awarded the Hermann Emminghaus Prize of the German Society for Child and Adolescent Psychiatry and Psychotherapy for her work on "Prevention, Early Intervention and Treatment of Computer Game and Internet Addiction in Adolescence". In 2020, she founded the Academy for Prevention Science, where currently 90 addiction professionals from all over Baden-Württemberg are trained as PROTECT trainers. In the AWMF guideline development on internet use disorders, she is in charge of the early intervention chapter.

Ulrike Basten is Professor of Biological Psychology at the University of Koblenz-Landau. After studying psychology at the Universities of Bielefeld, Exeter (UK) and Heidelberg, she started her PhD on personality-dependent differences in brain activation during the coping with cognitive challenges in Heidelberg, which she completed at Goethe University Frankfurt in 2011. It was also in Heidelberg that she discovered her interest in using biopsychological methods to investigate differential psychological issues. Her research focuses on how interindividual differences in brain structure and function are related to differences in cognitive abilities, personality, and mental health. Exploring the neural basis of intelligence and executive function is an important focus of her research. Through her brain imaging studies of intelligence, Basten has contributed to the development of models of the neural basis of human intelligence that attribute an important role to the activity and connectivity of a network of frontal, parietal, and subcortical brain regions in explaining individual cognitive performance. In the area of personality and mental health, Basten is concerned with interindividual differences in the ability to control attention and their importance for anxiety and resilience to the development of stress-related mental disorders.

Chapter 10
Metacognitive Myopia: An Obstacle to Intelligent Behavior and Lapse of the Evolution?

Klaus Fiedler, Florian Ermark, and Karolin Salmen

Abstract In cognitive psychology, those who behave in a particularly rational manner are considered intelligent. First, we briefly introduce the psychology of judgment and decision-making, which has played a key role in theorizing and empirical investigation of cognitive research for decades. We then give an impression of the pessimistic view of the rationality of human behavior that emerged from the research program of the two influential researchers, Daniel Kahneman and Amos Tversky. Yet, Herbert Simon's idea of bounded rationality provides an often-cited explanation of the many violations of mathematical and logical rules due to "heuristics and biases." This chapter highlights an alternative explanation that has traditionally received less attention: "metacognitive myopia" is a weakness in the metacognitive monitoring and control function that regulates our thinking. While numerous cognitive fallacies and misjudgments are recurrent and unavoidable, a comprehensive explanation of irrational behavior must also explain why biases and illusions are not detected and corrected at the metacognitive level, despite feedback and education. The uncritical and often naïve adherence to patently non-valid information is the subject of research on metacognitive myopia.

1 Introduction: Rationality as the Epitome of Intelligent Behavior

As is well known, one should not argue about nominal definitions, such as the concept of intelligence. Definitions are not right or wrong; they should simply be useful, for example, for scientific purposes. They should support communication (among scientists) instead of creating confusion and misunderstanding. In this sense, it can be useful to define intelligence operationally: as the ability that

K. Fiedler (✉) · F. Ermark · K. Salmen
Institute of Psychology, Heidelberg University, Heidelberg, Germany
e-mail: kf@psychologie.uni-heidelberg.de; florian.ermark@psychologie.uni-heidelberg.de; karolin.salmen@psychologie.uni-heidelberg.de

R. M. Holm-Hadulla et al. (eds.), *Intelligence - Theories and Applications*,
https://doi.org/10.1007/978-3-031-04198-3_10

intelligence tests measure. This definition enables us to compare mental performance between different individuals, nations, or over time (Flynn, 2007) through standardization. If, on the other hand, we value either creativity or perfection when selecting personnel, then it may be useful to define intelligence as problem-solving ability or as error avoidance. However, within cognitive psychology, behavior that satisfies the ideal of rationality is considered the epitome of intelligence.

1.1 Rational Judgment and Decision-Making

Rationality refers to the part of intelligence that Immanuel Kant dealt with in his Critique of Pure Reason (logic), Critique of Practical Reason (ethics and morals), and his Critique of Judgment (aesthetics). The concept of rationality also encompasses various definitions, for example, emphasizing coherence (inner coherence) or correspondence (conformity to external standards of quality). However, the noble ideal of rationality has little to do with general linguistic knowledge, numeracy, spelling, or other tasks commonly associated with intelligence. Rationality, in the Kantian sense, refers to the expediency of judgments, decisions, and actions. Over the past century, the study of rationality has fascinated not only psychologists but also scholars from various related disciplines such as philosophy, biology, anthropology, sociology, and behavioral economics, who are concerned with *judgment and decision making* (known by the acronym JDM). This field's fruitful engagement with rationality has not only shaped the development of modern behavioral science but has also earned several psychologists a Nobel Prize in economics. Judgment and decision making means evaluating different attitude objects (political parties; brand products; job applicants) or options (professions; holiday destinations; partners; lotteries) with regard to their expediency (i.e., their costs and benefits to be expected with specific probabilities).

To judge and decide rationally is—as Kant's well-known writings show—always connected with critique, with a critical weighing of various costs, benefits, and probabilities. Is the advantage of an attractive profession perhaps nullified by low pay or great competition and low probability of success? Is entering a lottery with a high prize sum worthwhile if there is a very low probability of winning? The critical weighing of the pros and cons can be so complex that an unequivocally correct solution may not exist. How much money is a human life worth? How much quality of life is one willing to give up in order to extend one's life by 1 year? In many other cases, however, a logically or psychologically correct answer is obvious. Not recognizing it is then considered a symptom of blatant irrationality. If one invests more money in the purchase of a commodity than one can achieve by selling it, one is not acting expediently; one who still behaves in this way is irrational. This is equally true for patients who take medications with lower efficacy than the severity of their side effects or for investors who believe they can make high profits without taking risks (Bazerman & Sezer, 2016). These problems are easily solvable with a little world knowledge and with common sense available to almost all humans.

1.1.1 The Pessimistic View of Humankind Since Kahneman and Tversky

It is not the tricky problems with no clear-cut solution, but the latter, much simpler problems that are the focus of rationality research that have led to a truly pessimistic view of human beings. Since the fundamental and overly influential work of Daniel Kahneman and Amos Tversky in the 1970s, thousands of empirical studies have addressed a provocative question: How can it be that people, largely regardless of education or IQ, violate indisputable rules of logic and statistics and seemingly ignore the simplest principles of rationality? In countless experiments, rationality research has compared human judgment and decision-making with normative rules of logic or mathematics and has repeatedly demonstrated how often people deviate from these norms.

1.1.2 Prominent Examples of Cognitive Errors and Illusions

Some prominent examples will illustrate how the rationality of behavior has been tested within the research program of Kahneman and Tversky (1972, 1973, 1984; Kahneman et al., 1982; Tversky & Kahneman, 1971, 1974, 1981). For instance, *preference reversals* have been found in numerous experiments (Slovic, 1995; Tversky, 1969). People consistently violate the symmetry assumption (they prefer A > B, but then B > A), or the transitivity assumption (they prefer A > B and B > C, but then C > A). The same pair of countries (USA and Canada) is judged to be both more similar and more different than another pair (Ceylon and Nepal) And, judgments depend on the comparison direction; asking about the similarity of North Korea to China yields higher values than asking about the similarity of China to North Korea (Tversky, 1977). Given two bets with the same expected value of 7€, people prefer the first bet, which has a 75% probability of winning 10€ (and a 25% chance of losing 2€), over the alternative bet, which has a 25% probability of winning 73€ (and a 25% chance of losing 15€). However, for the less preferred second bet, most people are willing to bet a higher amount than for the preferred first bet (Lichtenstein & Slovic, 1973; Slovic, 1995).

Another common and surprising example is the *conjunction fallacy*. It manifests itself in the frequently observed tendency to find the conjunction of two events more probable than one of the two events, which is logically impossible. For example, the number of blondes with blue eyes can never be greater than the number of blondes overall. Such examples of the conjunction fallacy are clear violations of probability theory or set theory. For example, most people consider it more likely that an earthquake in California will cause a tidal wave that costs 2000 lives than that a tidal wave will cost 2000 lives. Alternatively, the probability that an excellent tennis player will lose the first set but then go on to win the match is judged as higher than the probability that she will lose the first set (Tversky & Kahneman, 1983).

Many failures and cognitive fallacies are explained by heuristics. Heuristics are mental rules of thumb that allow for quick judgments but are often not very accurate. For instance, the phenomenon that quantitative estimates are closer toward an arbitrarily chosen initial value (anchor) compared to when there is no such anchor is called the *anchoring bias*. One explanation of this bias is that the initial value is used for estimation and then adjusted to a plausible value (*anchoring and adjustment heuristic*; Tversky & Kahneman, 1974). This heuristic can also explain other cognitive fallacies that are highly relevant and consequential in practice. For example, in the *planning fallacy, possibly because the costs of individual components of the project, which are naturally much lower, act as a low anchor and are not sufficiently adjusted in upward direction (Kruger & Evans,* 2004*).*

There are numerous other examples of heuristics that serve as explanations for cognitive illusions. According to the *availability heuristic* (Tversky & Kahneman, 1973), the probability and frequency of events that are readily available in memory (such as murder or struck by lightning as causes of death) are overestimated, while less available events (such as suicide or cardiovascular disease) are underestimated. While availability is often a good indication of the true frequency of events, it is also influenced by other factors (e.g., what causes of death we are more likely to learn about in the media and by hearsay compared to others), sometimes resulting in startling misperceptions.

1.1.3 Smart Through Simple Heuristics (Bounded Rationality)

Kahneman and Tversky's groundbreaking work established a rather pessimistic view of human intelligence and rationality. A little later, however, a countermovement emerged that interpreted the manifold findings of seemingly irrational behavior as actually adaptive (expedient for humans). From this changed perspective, heuristics are no longer sources of irrational behavior, but quick and economical tools (Gigerenzer, 2008) that underlie intelligent action: "heuristics that make us smart" (Gigerenzer et al., 1999). The manifold attempts to rationalize cognitive illusions and errors and to interpret them as symptoms of adaptive cognition are often based on Simon's (1990) idea of *bounded rationality*, according to which evolution has tailored our use of limited cognitive capacity to fulfill existing environmental demands. Artificial, intentionally difficult and misleadingly constructed tasks, typical of Kahneman and Tversky's research program, lie outside the natural domain of bounded rationality, and the apparent failures in such tasks are therefore not surprising (Juslin, 1994). The concepts of ecological (Todd & Gigerenzer, 2007) and social rationality (Hertwig et al., 2013) are recent derivatives of the bounded rationality concept.

A central implication of the assumption of bounded rationality is that judgment and decision-making competencies are often bound to the environments in which they were acquired. The errors of reasoning and cognitive illusions documented in the previous section usually occur when competencies tied to a particular learning environment are transferred to entirely different environments. A prominent example is the phenomenon of *overconfidence*, a systematically higher assessment of one's own precision than is actually justified. For example, when laypeople or even experts believe that they are 90% correct in their judgments, correctness amounts to only 70%. Judges can be well calibrated with respect to clearly defined task domains; however, they overestimate themselves when they transfer their domain-specific calibration to new domains (Gigerenzer et al., 1991; Juslin, 1994).

2 Metacognition

Meanwhile, the ability to transfer competencies to new domains is hardly an artificial task, but a natural requirement of adaptive intelligence. Environments change constantly, and individuals (organisms) change their locations, social environments, organizations and learning institutions. Excusing failures by a change of environment is therefore not convincing. The criterion of flexibility and transferability of competencies to new domains represents a special requirement for rational behavior, which needs a constant critical examination of the environment by the individual. This capacity is called metacognition. It is the focus of our own research on the rationality of human judgment and decision-making.

2.1 Quality Control of One's Own Thinking

Metacognition does not operate separately from the rest of cognition, but is a central part of it. It takes over the quality control of mental functions, the *monitoring* and *control* of thinking and memory (Ackerman & Thompson, 2017; Nelson & Narens, 1990). These metacognitive functions are in particular demand when circumstances change, so that the question arises whether old competencies are still appropriate or need to be replaced by new ones.

2.1.1 Monitoring and Control

The surveillance function of intelligence is ubiquitous. Every sentence we speak or write, every document we sign, every purchase we make, we can review and edit, if only to avoid careless errors. This should be done all the more frequently when we are thinking about significant judgments, conclusions, evidence, and momentous decisions (Ackerman & Thompson, 2017). The results of the monitoring function form the input for the control function, which retains and enacts designs found to be correct while withholding, discarding, or correcting faulty designs.

2.1.2 Possibility of Correction and Learning

This possibility of correcting erroneous judgments and decisions after the fact has been widely overlooked, or at least severely neglected, in rationality research in the Kahneman–Tversky tradition. While the illusions and biases induced by heuristics initially deviate from the norms of rationality, they can be corrected through metacognitive quality control. Just as we can correct a typo in a letter or even an incorrect answer on a test, and just as it is ultimately not the initial error but the satisfactory final result that counts, monitoring and controlling significant judgments and decisions is, after all, an important facet of intelligent, rational action. When we recognize our decisions, judgments, and perceptions as wrong or out of touch with reality, especially when it is possible for us to make a clear improvement by correction, the measurement of rationality must be sensitive to whether the need for correction is recognized and changes are implemented accordingly. Even if an initial error cannot be (fully) corrected, for example, because its cause is not yet understood, the metacognitive process can at least avoid wrong conclusions with unnecessary costs. For example, if a new corporate strategy leads to clear losses, senior managers may refrain from applying the strategy, regardless of whether they fully understand the cause and correct for the failure (e.g., a fraud in the stock market environment or a faulty market analysis) or whether only the costs are apparent. However, it is precisely this self-evident role of metacognition that has been largely neglected in rationality research. As will become apparent below, a comprehensive theoretical conception of rational behavior must explain not only how erroneous initial judgments and decisions (under time pressure or without sufficient attention or care) can arise. Such errors in the first draft are hardly worth mentioning, if they are corrected. Therefore, a comprehensive theory of rational action must explain whether and under what conditions such errors are recognized and corrected, and when, through a combination of faulty cognition and deficient metacognitive control, harm actually occurs to the individual.

2.2 Metacognitive Myopia

Looking at the results of metacognition research so far, it becomes apparent that deficits in the monitoring and control of one's own mental operations are widespread and have serious consequences. Metacognitive myopia turns out to be one of the most severe obstacles on the way to rational behavior. Despite our limited cognitive resources, judgments and decisions can often be made surprisingly well even on the basis of complex data (e.g., when a teacher has to evaluate the performance of diverse students in many classes and different subjects; Fiedler et al., 2002, 2007). Even though, or exactly because, the participants in many experiments manage to process the data effectively, metacognitive myopia—the naïve and uncritical tendency to take information at face value regardless of its validity—leads to persistent errors and clear violations of rational principles. The following sections provide some insight into relevant findings on metacognitive myopia (for a more detailed review, see, e.g., Fiedler, 2000, 2012).

2.2.1 Uncritical Correspondent Inferences

A memorable "classic" example can be found in an old study by Jones and Harris (1967) on *correspondence bias* (also known as fundamental attribution error). Participants read essays about Fidel Castro and were asked to infer the author's attitude toward the Cuban president and his politics at the time. Not surprisingly, participants inferred a positive attitude from pro-Castro essays and a negative attitude from anti-Castro essays. What was less natural, however, was that participants attributed a corresponding attitude to the authors even when they knew that the authors were not free to decide whether to write pro or contra Fidel Castro. Even when the content of the essay could not be diagnostic for the attitude, the content was used—against better knowledge and in an uncritical way—as a source of information. Recent findings on the naïve adherence to obvious fake news, despite clear debriefing (Lewandowsky et al., 2012), are hardly surprising against this background.

2.2.2 Perseverance

Similar to this observation, it can be shown in many areas that (mis)information continues to have an effect even after its unreliability has been clarified (*perseverance*). In a study by Ross et al. (1975), participants were asked to estimate whether a statement was true. Afterward, they were told that their assessment was correct or incorrect. Note that this feedback was completely independent of the person's actual performance. A low (high) error rate reported back to the participants was intended to create a positive (negative) impression of their performance. After the assessments were completed, the participants were debriefed that the feedback they just received had no significance whatsoever. Nevertheless, participants who had received fake positive feedback subsequently rated themselves more positively than the victims of the fake negative feedback, despite the debriefing that their actual performance did not differ. This perseverance of clearly invalidated information was evident not only among the participants themselves but also among uninvolved observers. It could only be reduced but not fully eliminated by warnings about perseverance. Persistent evidence for incomplete debunking effects, regardless of education and revelation interventions, is a frequently discussed, prominent research topic problem, especially with regard to social media (e.g., Chan et al., 2017).

2.2.3 Inability Not to Learn

In everyday life, people often encounter information multiple times, whether it is misinformation on social media, advertising, or news reports. Of course, the frequency of viewing does not change the content: once all information has been absorbed, all further repetitions become redundant. Thus, further encounters should not lead to further learning. However, once again, research shows that although individuals can distinguish between new information and repetition, repetition still influences their decisions. Unkelbach et al. (2007) showed individuals the performance (positive/negative) of fictitious stocks. For some days, the same information was shown twice, in two different news programs. Despite the warning not to be influenced by such duplications, subsequent assessments of the stocks were biased toward the repeated information. This bias also triggered disadvantageous decision intentions. Only when participants worked on another task at the same time, which put a strain on their working memory, there was less influence of redundant information. If the participants were forced to divide their limited attention, they were better able to direct it specifically to the relevant, new information.

2.2.4 Inability Not to Remember

Those who forget as little as possible are often considered intelligent. This neglects the fact that short- or long-term forgetting is also part of an efficient use of memory, if this is advantageous. This is not only true for "deleting" or "overwriting" misinformation, as illustrated in the section on perseverance. For example, if a selection committee learns by accident that an applicant is pregnant, that information should not affect the hiring process. Can such a state of *deliberate ignorance* be induced after information is already known? Numerous studies suggest that even in this area metacognition remains too myopic and the influence of impermissible memories cannot be reliably avoided (for an overview on not wanting to know and not wanting to remember, see Hertwig & Engel, 2020).

However, it seems even more problematic to vividly remember what has never been seen and experienced. Research on *constructive memory* impressively demonstrates the frequency and regularity with which such false memories can arise. For example, Loftus et al. (1978) showed their participants videos of a traffic accident at an intersection where there was yield sign. After subsequent questioning, participants who were asked "Did another car pass the red Datsun while it was stopped at the stop sign?" later erroneously confirmed the car passing a stop sign than participants for whom the question correctly referred to a yield sign. In another example (Fiedler et al., 1996), participants were more likely to believe that a person they were observing had engaged in negative behaviors when asked about those behaviors beforehand, even when they had initially (correctly) denied them. Thus, metacognition does not prevent memories from being altered and added to by undue influences, nor do our inferences take the constructive nature of memories into account.

2.3 A Question of Usefulness and Relevance?

The approach of bounded rationality presented above should also make us question metacognition research. Are the effects shown possibly due to the constructed laboratory conditions? Do they also show up in everyday life? How great is the significance of metacognitive myopia for our daily actions, how much does effective metacognition benefit us? Along these lines, we will now assess the significance of metacognitive myopia in important applied contexts, where much is at stake and metacognition can help to avoid greater harm.

2.3.1 Assessment of Witness Statements

An impressive example is a method used by experts in criminal trials to test the credibility of witness statements. The judge's verdict of guilt in many proceedings in which no physical evidence exists (such as rape or other sexual offences) depends on such expert opinions. In the method of *Criteria-Based Statement Analysis* (CBSA; Vrij, 2005), experts count the number of so-called truth criteria in a witness statement. However, it is not taken into account that the expected number of these linguistic truth indicators depends decisively on the length of the text. In a longer testimony of 20 pages one naturally finds more truth criteria than in a short text of only one page. Even after this obvious problem was pointed out to them, legal experts resisted the criticism and continued to base existentially important expert opinions on an uncritical CBSA count (Fiedler & Prokop, 2002). Thus, metacognitive myopia is evident in everyday life and in a particularly important task at that.

2.3.2 Assessment of Risks and Advice

Misjudging the risks and opportunities associated with different courses of action in everyday life, such as vaccinations and other medical treatments, and the incorrect and uncritical use of advice from (real or supposed) experts, can be life-threatening. How well do we distinguish between helpful and harmful advice in such circumstances? In a study by Fiedler et al. (2019), participants were first asked to assess different health risks, such as the likelihood of having breast cancer if a mammogram was abnormal. Then they received advice from experts, which included both an estimate of the risk and an explanation of the estimate. This explanation indicated that some advice was based on a reliable sample, but some was based on a biased sample (and was therefore poor advice). The participants' final risk assessments showed that many of them included all advice uncritically, regardless of its reliability—sometimes even when bad advice was accompanied by an unambiguous warning. Despite the significance and everyday relevance of these assessments, neither adequate monitoring nor control of erroneous information was evident. These effects of metacognitive myopia can cost individuals their lives.

To properly understand this memorable phenomenon, it is important to note that individuals do possess the necessary cognitive capacities to perform the metacognitive monitoring and control functions. Thus, they do not lack the intelligence necessary to understand the fallibility of false or misleading information.

2.3.3 Democratic Decision Making

Decisions in groups, be it a parliamentary vote on a legislative package or the selection of new roommates in a shared apartment, represent another everyday challenge to metacognition. A particularly relevant bias here is the increased influence of repeated information mentioned above. If the same argument is brought up multiple times in a discussion, it is weighted much more heavily than arguments that are brought up less frequently but are just as relevant. In a study by Fiedler et al. (2018), for example, a fictitious discussion was shown in which the current residents of a shared apartment exchanged observations on the positive and negative characteristics of four different applicants for a room. They repeatedly and selectively repeated information that benefited some applicants and harmed others. The participants' evaluations based on this information were more strongly influenced by the repeated information, although it did not have a higher relevance—this influence was so strong that objectively worse applicants were preferred. This effect persisted even when participants were explicitly told that repeated information did not add any novel evidence and should not be given special consideration, or when the information was repeated multiple times by only one person, thus not signaling social approval by several others. It was also of little use if the subjects were warned that the repetition of statements was done with manipulative intent.

In general, it may well be useful to give more weight to repeated information—for example, if the repetition is actually correlated with the truth value, for instance, if repetition means social validation. However, when this is not the case, lack of monitoring and control inevitably renders majority opinions more influential than positions contributed by minorities, regardless of their substantive quality (Fiedler et al., 2015). Here, metacognitive myopia hinders the unfolding of the potential inherent in group-based and democratic decision-making processes.

2.4 Improving Metacognitive Performance

Legal applications, medical risk assessments and democratic decision-making processes show impressively how important critical metacognition is, but also that it often falls short or fails completely. Looking at these results, one cannot help but ask about ways to improve it. Can we train metacognition and thus improve thinking and acting?

The previous sections give rise to tentative pessimism. The initial idea that suggests itself in the spirit of the Enlightenment, that an explanation of these shortcomings is sufficient to overcome the metacognitive immaturity, seems condemned to fail. However, this impression also hinges on the expectation that this intervention would have to completely eliminate metacognitive myopia, although even a partial reduction could represent an important improvement. In an exciting recent example, Schmid and Betsch (2019) showed that the influence of false arguments from vaccination skeptics on the audience could be significantly reduced by having another person present substantive counterarguments but also by simply explaining the rules that the argument violates. One possible way to improve metacognition is to change the environment, thereby creating favorable conditions. This includes clear and rapid feedback, incentives for improvement, and preemptive consolidation of well-confirmed information. For example, deepening correct beliefs (e.g., about vaccination) through confirmation and engagement sensitizes individuals for the inadmissibility of arguments and protects them from subsequent manipulation attempts (*inoculation theory*; see, e.g., Banas & Rains, 2010).

3 Conclusions

Without losing all optimism about the trainability of metacognitive skills,[1] the memorable insight remains that metacognitive myopia constitutes a major obstacle for rational thought and action. If we lack this critical judgment skill—monitoring information to differentiate between obviously false information or fake news and genuine, persuasive information, and the appropriate control to respond and adequately correct information—the question arises as to why this crucial competence has not been evolutionarily formed.

In the absence of a complete and definitive answer, at least some plausible considerations suggest themselves. First, it must be seen that metacognition—the ability to think about possible alternative worlds and probabilities—is a very recent Enlightenment invention whose development is still in its infancy. Second, metacognitive myopia may reflect what Robin Hogarth and colleagues have called "*wicked environments*" (Hogarth et al., 2015), namely the scarcity of feedback and the frequency with which the environment gives us no feedback at all, or only very late or indirect feedback about our judgments and decisions. Apart from this, perhaps the most interesting answer is that evolution may not have "forgotten" to strengthen metacognition but may have "deliberately" suppressed it. After all, the mathematical algorithms necessary to correct probabilistic assumptions are poorly understood, and the cost of notoriously criticizing dubious information may be higher than its benefit. The constant attempt to question and critically test the durability of every piece of information could mean sacrificing a number of other tenets of adaptive intelligence, such as unquestioned trust in social information, parsimonious heuristics, and rapid, automatic priming effects.

[1] A very informative overview of the transfer of promising findings from cognitive research can be found in Metcalfe and Kornell (2007).

References

Ackerman, R., & Thompson, V. A. (2017). Meta-reasoning: Monitoring and control of thinking and reasoning. *Trends in Cognitive Sciences, 21*(8), 607–617. https://doi.org/10.1016/j.tics.2017.05.004

Banas, J. A., & Rains, S. A. (2010). A meta-analysis of research on inoculation theory. *Communication Monographs, 77*(3), 281–311. https://doi.org/10.1080/03637751003758193

Bazerman, M. H., & Sezer, O. (2016). Bounded awareness: Implications for ethical decision making. *Organizational Behavior and Human Decision Processes, 136*, 95–105. https://doi.org/10.1016/j.obhdp.2015.11.004

Chan, M. S., Jones, C. R., Hall Jamieson, K., & Albarracín, D. (2017). Debunking: A meta-analysis of the psychological efficacy of messages countering misinformation. *Psychological Science, 28*(11), 1531–1546. https://doi.org/10.1177/0956797617714579

Fiedler, K. (2000). Beware of samples! A cognitive-ecological sampling approach to judgment biases. *Psychological Review, 107*(4), 659.

Fiedler, K. (2012). Meta-cognitive myopia and the dilemmas of inductive-statistical inference. In B. H. Ross & B. H. Ross (Eds.), *The psychology of learning and motivation* (Vol. 57, pp. 1–55). Elsevier Academic Press. https://doi.org/10.1016/B978-0-12-394293-7.00001-7

Fiedler, K., Armbruster, T., Nickel, S., Walther, E., & Asbeck, J. (1996). Constructive biases in social judgment: Experiments on the self-verification of question content. *Journal of Personality and Social Psychology, 71*(5), 861–873. https://doi.org/10.1037/0022-3514.71.5.861

Fiedler, K., Freytag, P., & Unkelbach, C. (2007). Pseudocontingencies in a simulated classroom. *Journal of Personality and Social Psychology, 92*(4), 665–677. https://doi.org/10.1037/0022-3514.92.4.665

Fiedler, K., Hofferbert, J., & Wöllert, F. (2018). Metacognitive myopia in hidden-profile tasks: The failure to control for repetition biases. *Frontiers in Psychology, 9*, 903. https://doi.org/10.3389/fpsyg.2018.00903

Fiedler, K., Hofferbert, J., Wöllert, F., Krüger, T., & Koch, A. (2015). The tragedy of democratic decision making. In *Social psychology and politics* (pp. 193–208). Psychology Press.

Fiedler, K., Hütter, M., Schott, M., & Kutzner, F. (2019). Metacognitive myopia and the overutilization of misleading advice. *Journal of Behavioral Decision Making, 32*(3), 317–333. https://doi.org/10.1002/bdm.2109

Fiedler, K., & Prokop, I. (2002). *Some psychometric problems of criteria-based statement analysis: Codability, discriminant validity, and the need to control for text-length artifacts*. Unpublished research, Heidelberg University.

Fiedler, K., Walther, E., Freytag, P., & Plessner, H. (2002). Judgment biases in a simulated classroom - A cognitive-environmental approach. *Organizational Behavior and Human Decision Processes, 88*(1), 527–561. https://doi.org/10.1006/obhd.2001.2981

Flynn, J. R. (2007). *What is intelligence? Beyond the Flynn effect*. Cambridge University Press.

Gigerenzer, G. (2008). Why heuristics work. *Perspectives on Psychological Science, 3*(1), 20–29.

Gigerenzer, G., Hoffrage, U., & Kleinbölting, H. (1991). Probabilistic mental models: A Brunswikian theory of confidence. *Psychological Review, 98*(4), 506–528. https://doi.org/10.1037/0033-295X.98.4.506

Gigerenzer, G., Todd, P. M., & the ABC Research Group. (1999). *Simple heuristics that make us smart*. Oxford University Press.

Hertwig, R., & Engel, C. (Eds.). (2020). *Deliberate ignorance: Choosing not to know*. The MIT Press.

Hertwig, R., Hoffrage, U., & the ABC Research Group. (2013). *Simple heuristics in a social world*. Oxford University Press. https://doi.org/10.1093/acprof:oso/9780195388435.001.0001

Hogarth, R. M., Lejarraga, T., & Soyer, E. (2015). The two settings of kind and wicked learning environments. *Current Directions in Psychological Science, 24*(5), 379–385.

Jones, E. E., & Harris, V. A. (1967). The attribution of attitudes. *Journal of Experimental Social Psychology, 3*(1), 1–24. https://doi.org/10.1016/0022-1031(67)90034-0

Juslin, P. (1994). The overconfidence phenomenon as a consequence of informal experimenter-guided selection of almanac items. *Organizational Behavior and Human Decision Processes, 57*(2), 226–246. https://doi.org/10.1006/obhd.1994.1013

Kahneman, D., Slovic, P., & Tversky, A. (Eds.). (1982). *Judgment under uncertainty: Heuristics and biases*. Cambridge University Press.

Kahneman, D., & Tversky, A. (1972). Subjective probability: A judgment of representativeness. *Cognitive Psychology, 3*(3), 430–454. https://doi.org/10.1016/00100285(72)90016-3

Kahneman, D., & Tversky, A. (1973). On the psychology of prediction. *Psychological Review, 80*(4), 237.

Kahneman, D., & Tversky, A. (1984). Choices, values, and frames. *American Psychologist, 39*(4), 341–350. https://doi.org/10.1037/0003-066X.39.4.341

Kruger, J., & Evans, M. (2004). If you don't want to be late, enumerate: Unpacking reduces the planning fallacy. *Journal of Experimental Social Psychology, 40*(5), 586–598. https://doi.org/10.1016/j.jesp.2003.11.001

Lewandowsky, S., Ecker, U. K. H., Seifert, C. M., Schwarz, N., & Cook, J. (2012). Misinformation and its correction: Continued influence and successful debiasing. *Psychological Science in the Public Interest, 13*(3), 106–131. https://doi.org/10.1177/1529100612451018

Lichtenstein, S., & Slovic, P. (1973). Response-induced reversals of preference in gambling: An extended replication in Las Vegas. *Journal of Experimental Psychology, 101*(1), 16–20. https://doi.org/10.1037/h0035472

Loftus, E. F., Miller, D. G., & Burns, H. J. (1978). Semantic integration of verbal information into a visual memory. *Journal of Experimental Psychology: Human Learning and Memory, 4*(1), 19–31. https://doi.org/10.1037/0278-7393.4.1.19

Metcalfe, J., & Kornell, N. (2007). Principles of cognitive science in education: The effects of generation, errors, and feedback. *Psychonomic Bulletin & Review, 14*(2), 225–229.

Nelson, T. O., & Narens, L. (1990). Metamemory: A theoretical framework and new findings. In G. H. Bower (Ed.), *Psychology of learning and motivation* (Vol. 26, pp. 125–173). Elsevier Academic Press. https://doi.org/10.1016/S0079-7421(08)60053-5

Ross, L., Lepper, M. R., & Hubbard, M. (1975). Perseverance in self-perception and social perception: Biased attributional processes in the debriefing paradigm. *Journal of Personality and Social Psychology, 32*(5), 880–892. https://doi.org/10.1037/0022-3514.32.5.880

Schmid, P., & Betsch, C. (2019). Effective strategies for rebutting science denialism in public discussions. *Nature Human Behaviour, 3*(9), 931–939. https://doi.org/10.1038/s41562-019-0632-4

Simon, H. A. (1990). Bounded rationality. In J. Eatwell, M. Milgate, & P. Newman (Eds.), *Utility and probability* (pp. 15–18). Palgrave Macmillan. https://doi.org/10.1007/978-1-349-20568-4_5

Slovic, P. (1995). The construction of preference. *American Psychologist, 50*(5), 364–371. https://doi.org/10.1037/0003-066X.50.5.364

Todd, P. M., & Gigerenzer, G. (2007). Environments that make us smart: Ecological rationality. *Current Directions in Psychological Science, 16*(3), 167–171. https://doi.org/10.1111/j.1467-8721.2007.00497.x

Tversky, A. (1969). Intransitivity of preferences. *Psychological Review, 76*(1), 31–48. https://doi.org/10.1037/h0026750

Tversky, A. (1977). Features of similarity. *Psychological Review, 84*(4), 327–352. https://doi.org/10.1037/0033-295X.84.4.327

Tversky, A., & Kahneman, D. (1971). Belief in the law of small numbers. *Psychological Bulletin, 76*(2), 105–110. https://doi.org/10.1037/h0031322

Tversky, A., & Kahneman, D. (1973). Availability: A heuristic for judging frequency and probability. *Cognitive Psychology, 5*(2), 207–232.

Tversky, A., & Kahneman, D. (1974). Judgment under uncertainty: Heuristics and biases. *Science, 185*(4157), 1124–1131. https://doi.org/10.1126/science.185.4157.1124

Tversky, A., & Kahneman, D. (1981). The framing of decisions and the psychology of choice. *Science, 211*(4481), 453–458. https://doi.org/10.1126/science.7455683

Tversky, A., & Kahneman, D. (1983). Extensional versus intuitive reasoning: The conjunction fallacy in probability judgment. *Psychological Review, 90*(4), 293.

Unkelbach, C., Fiedler, K., & Freytag, P. (2007). Information repetition in evaluative judgments: Easy to monitor, hard to control. *Organizational Behavior and Human Decision Processes, 103*, 37.

Vrij, A. (2005). Criteria-based content analysis: A qualitative review of the first 37 studies. *Psychology, Public Policy, and Law, 11*(1), 3–41.

Klaus Fiedler has been Professor of Social Psychology at Heidelberg University since 1992. He investigates the relationship between language and cognition, cognition and behavioral regulation, judgment and decision-making, and learning in complex systems. His findings open up the possibility of using linguistic patterns to infer lies and improve the reliability of lie detectors. With his cognitive-ecological approach to decision research, he tries to find answers to pressing questions of the modern information society, which is characterized by an overabundance of information. In 2000, he was awarded the Leibniz Prize of the German Research Foundation and the Psychology Prize of the German Psychological Society for his work. He has been a member of the National Academy of Sciences (Leopoldina) since 2002 and a member of the Heidelberg Academy of Sciences since 2003.

Florian Ermark is a research associate and doctoral student at the Social Psychology Unit (CRISP) at Heidelberg University. After his Bachelor in Psychology at the University of Konstanz, he completed an M.Sc. in Psychology at the Heidelberg University. He conducts research and gives courses on judgment and decision-making, especially in a collective context, information processing, and inductive reasoning with aggregated evidence.

Karolin Salmen is a research associate and is doing her PhD on serial reproduction (Social Psychology Unit) at the Heidelberg University. After a bachelor's degree in psychology in Münster and exchange studies at Peking University, China, she completed master's degrees in psychology (Heidelberg University) and social cognition (University College, London). She conducts research and gives courses on the influence of communication on cognition, as well as collective and social information sharing, reasoning, and decision making.

Part III
Mathematical and Artificial Intelligence

Chapter 11
How Smart Are Equations and Algorithms?: An Attempt to Transfer the Notion of Intelligence to Mathematical Concepts

Thomas Stiehl and Anna Marciniak-Czochra

Abstract This chapter is devoted to the question of whether mathematical intelligence exists and what it might be. Using simple textbook examples and applications from current research, we point out similarities and differences between mathematical intelligence and its human counterpart. We focus on so-called mechanistic mathematical modeling. Mechanistic modeling leverages mathematical and computational methods to study how complex phenomena arise from basic principles. It enables a systematic and quantitative analysis of a broad range of questions.

1 What Is Intelligence?

Intelligence is a frequently used but rarely defined term. Different definitions have been developed by psychologists and neuroscientists. Possibly, the so-called operationalist approach is the lowest common denominator of the existing definitions. It defines intelligence as what an intelligence test verifies (Boring, 1923). This definition is mentioned in many clinical textbooks such as (Plante, 2005) and provides important clues about what is referred to as "intelligence." Common intelligence tests, e.g., the Hamburg-Wechsler Intelligence Scales (HAWIE/HAWIK or WAIS-IV (Wechsler, 2008)), consist of questions from different areas which a subject has to answer. Thus, intelligence can be defined as the *ability to* "correctly" answer questions from different areas. This view is in good agreement with the rather explicit

T. Stiehl
Institute for Computational Biomedicine – Disease Modeling, RWTH Aachen University & RWTH Aachen Medical School, Aachen, Germany
e-mail: tstiehl@ukaachen.de

A. Marciniak-Czochra (✉)
Institute of Applied Mathematics, Heidelberg University, Heidelberg, Germany
e-mail: anna.marciniak@iwr.uni-heidelberg.de

R. M. Holm-Hadulla et al. (eds.), *Intelligence - Theories and Applications*,
https://doi.org/10.1007/978-3-031-04198-3_11

definition from (Gottfredson, 1997) which is referred to in standard textbooks (Gerrig, 2013). It defines intelligence as a "very general mental capability that, among other things, involves the ability to reason, plan, solve problems, think abstractly, comprehend complex ideas, learn quickly and learn from experience" (Gottfredson, 1997).

In the following, we will define *mathematical intelligence* as the ability of mathematical or algorithmic structures to realize one or more of the capabilities listed above (i.e., to answer questions correctly, to solve problems, to learn from experience, to comprehend complex ideas, etc.). We are aware that the use of the term intelligence in relation to algorithms and mathematical concepts represents an anthropomorphism, i.e., human characteristics are attributed to non-human entities. Such an attribution may be motivated by specific analogies; however, in most cases there is no comparability in the strict sense. Bearing in mind that there are significant differences between human intelligence and current mathematical or artificial intelligence, we discuss similarities between the two. This approach entails the application of further humanistic terms to abstract constructs. In the new context, these terms may not necessarily have unambiguous and straightforward definitions.

2 Why Do We Need Mathematical Intelligence?

The predictive and explanatory ability of mathematical modeling plays an important role when phenomena are inaccessible by human intuition. This can result from different aspects, for example,

1. A process is highly complex, i.e., its dynamics are determined by the interaction of a large number of variables that often interact in a non-linear manner. *Example*: The properties of blood stem cells after bone marrow transplantation depend on patient-specific and transplant-specific factors. Stem cell properties are regulated by hormonal signals that nonlinearly depend on system variables. This makes it difficult to intuitively understand how stem cell properties evolve in time. Mathematical models make it possible to link clinical observations to stem cell properties (Østby et al., 2003; Marciniak-Czochra et al., 2009; Stiehl et al., 2014; Manesso et al., 2013).
2. The exact interaction of essential system components is not (yet) known in sufficient detail. *Example*: It is unclear which chemical, physical and biological processes govern pattern formation in developmental biology. Mathematical models provide clues as to which components of intra- and intercellular signaling may be responsible for a particular patterning of tissues. These insights contribute to the understanding and design of experiments (Mercker et al., 2021a; Turing, 1952; Hiscock & Megason, 2015).
3. Relevant information is missing, e.g., because important parameters cannot be measured or because of low temporal or spatial resolution of experimental data.

Example: For many types of cancer it is not possible to characterize or observe cancer stem cells in vivo (in the patient). Furthermore, data can only be collected during the relatively infrequent follow-up examinations. Solving inverse problems for mathematical models (so-called parameter estimation) helps to quantify unknown parameters and unobservable processes (Stiehl et al., 2015, 2020; Kather et al., 2017, 2018).

4. Data sets consist of a large number of variables and the amount of data exceeds human comprehension. *Example*: Which changes measured in gene expression studies are relevant to an observed biological process? Such questions can be answered by computational algorithms that allow identifying likely scenarios (Ravichandran & Del Sol, 2017).
5. Different hypothetical mechanisms could serve as plausible explanations for an observed phenomenon. Mathematical modeling can help to choose the most realistic out of several competing hypotheses. *Example*: It is unclear how the properties of neural stem cells in the brain change during aging; possible scenarios include age-related changes of the mortality rate, of the activation rate, of the division rate, or of the differentiation rate. Different hypotheses can be investigated using a model selection approach (Kalamakis et al., 2019; Burnham & Anderson, 2002).

Mathematical intelligence can be seen as a tool that supports and enhances human reasoning, decision-making, predictive skills, and knowledge acquisition. Even if the techniques of mathematical intelligence work perfectly, the identification of the questions to be investigated, the overall goals of the research, and the selection of the data used to answer a given question will be a result of human intelligence.

3 What Is Mechanistic Modeling and on What Basic Ideas Is It Based?

Mechanistic modeling is also referred to as *process-driven modeling*. Mechanistic models are a translation of processes and mechanisms into formal objects. This translation allows studying a given problem using mathematical and computational tools (Fig. 11.1). The dynamics under consideration are quantified by so-called *process parameters*, which determine the speed (rate) of the respective processes. The resulting formal objects are, e.g., mathematical equations, algorithms, or computer programs. A classic example of a mechanistic model is the mathematical formulation of Newton's axioms and their application to problems from classical mechanics.

The advantage of the formal problem representation is its accessibility by mathematical and computational tools. These tools allow systematically characterizing and predicting the effect of the modeled processes on the dynamics of a complex system. Modeling makes a practical problem accessible to the inherent logics of mathematical theories and to the efficiency of computational methods. Existing

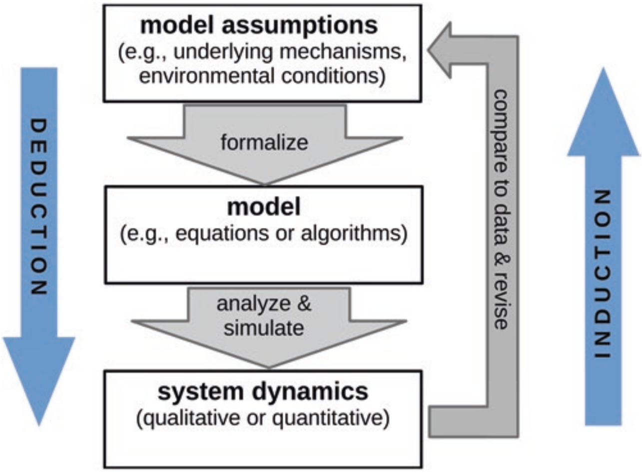

Fig. 11.1 Principle of mechanistic modeling. (Source: Own figure)

knowledge is incorporated into mechanistic models in the form of the modeled processes and their parameters.

Using computer simulations and mathematical analysis, process modeling allows systematically exploring how observable system dynamics depend on the model assumptions and the underlying mechanisms. During *model validation,* model dynamics are compared to data and potential disagreements between model and reality are revealed. Ideally, each model is additionally validated by predicting the outcome of novel experiments and by confirming the prediction based on new data.

From the epistemological point of view, a mechanistic model cannot be proof of the correctness of a hypothesis. If a given model perfectly fits to all available data, it can be concluded that the observed data is *compatible with* the given model. However, alternative models could lead to an equally good or even better fit. Noteworthy, incorrect model assumptions can also lead to correct predictions, as demonstrated by the luminiferous ether, the existence of which was disproved years after it was postulated (Shankland, 1964). The impossibility to prove the correctness of a hypothesis is not specific to mathematical modeling, it is rather a common property of all theories which are based on empirical observations. Therefore, a model can be considered valid only until it leads to an incorrect prediction.

If the predictions of a model do not agree with observations, the model can be falsified. This implies that at least one of the underlying model assumptions is incorrect, i.e., the mechanisms considered in the model are insufficient to explain observations. This problem often arises because key interactions have not been accounted for or are yet unknown. In this case, the model has to be revised. Disagreements between model and data have the potential to advance research since they indicate gaps of knowledge and incorrectness of the current theories. Models can help to close knowledge gaps by providing information about the qualitative effects of yet unknown mechanisms, e.g., by proposing interactions that could reconcile theory with observations.

In summary, mechanistic modeling is an abstract machinery that uses mathematical and computational methods to transform model assumptions into hypothetical system behavior. The latter can be compared to data. Such a comparison helps to reveal which mechanisms might be responsible for which observed phenomena. The obtained insights contribute to the generation of new hypotheses and to the design of future experiments.

4 What Are Applications of Mechanistic Models?

Mechanistic mathematical modeling can be applied to a wide spectrum of problems from various disciplines, including biology, physics, medicine, pharmacy, chemistry, and economics. To illustrate the principles of mechanistic modeling, its applications, and its relation to the definition of intelligence, we start our considerations with a simple textbook example.

4.1 A Simple Example

A very early and instructive example of mechanistic modeling is the exponential growth of a bacterial population in a well-mixed medium. Let us assume that all bacteria have identical properties, do not die and undergo a constant number of divisions per unit of time. If sufficient nutrients are available in the medium, we will observe the well-known exponential growth law, which describes the number of bacteria per milliliter of medium over time.

The exponential growth curve is a very simple example of a mechanistic mathematical model. The first important model parameter is number of bacteria per milliliter of medium at the beginning of the experiment, also referred to as *initial condition*. The second important model parameter is the growth rate which essentially describes how often the bacteria divide per unit of time. It is an example for a *process parameter*. The model allows quantifying the growth dynamics of the bacterial population as a function of initial conditions and process parameters. The obtained model can be applied in different contexts, as we will detail in the following sections.

4.2 Quantification and Parameter Estimation

Let us assume that we dispose of measurements that quantify the exponential growth of a bacterial concentration. Together with the model such data enables us to estimate the growth rate of the bacterial population. For this purpose, we vary the growth rate in the model until the model output optimally fits to the given data. Such an approach is referred to as *parameter estimation (*Nieman et al., 1971*)* (Fig. 11.2a). Parameter estimation combines mechanistic models and data to *quantify* parameters that cannot be measured directly. In our example the model allows to quantify the division rate of the bacteria, i.e., the model is capable of solving a quantification problem. To do so it incorporates existing knowledge (in terms of biological processes, i.e., cell division) and experimental data. Phrased differently: the model can infer the unknown division rate from the assumed processes and the given data. Or:

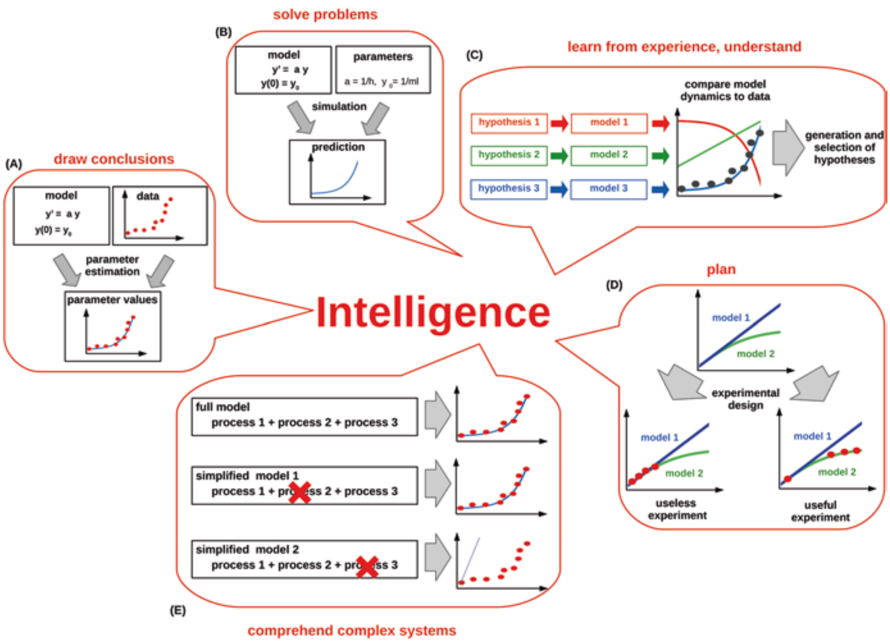

Fig. 11.2 Constituting features of intelligence related to properties of mechanistic models. (**a**) Reasoning/Drawing logically sound conclusions: During parameter estimation parameter values are inferred from model and data. (**b**) Problem solving: Validated and parameterized mechanistic models can predict the behavior of a system and thus solve prediction and optimization problems. (**c**) Learning from experience: Based on experience (here in the form of data), model selection can be used to "learn" which model is most likely to fit reality. (**d**) Planning: Models can be used to plan at what times measurements need to be performed in order to optimally answer a given question. In the example shown, the goal is to plan an experiment that allows rejecting one of the two models. Measured values are shown as red dots. (**e**) Comprehend complex problems: Systematic and rigorous simplifications of a complex model (model reduction) reveal which processes trigger which phenomena. (Source: Own figure)

the model "learns" the growth rate based on the experience of the underlying biological processes and the experimental measurements. Problem solving, reasoning, and learning from experience are characteristics of intelligence according to the definition stated in Sect. 1.

In practice only a limited number of parameters can be reliably estimated based on a given dataset. Therefore, mathematical models usually are a trade-off between model complexity, available data, and the question of interest. It has to be carefully considered which processes should be modeled in which level of detail and which variables are relevant. For real world applications, specific simple models are often preferable to a complex but more general model.

4.3 Predictions

Knowing the initial concentration of bacteria and their doubling rate, the model of bacterial growth can *predict* how long it takes to reach a given bacterial concentration, supposed that model assumptions are not violated. Quantitative models with known parameters can be used to plan experiments (Fig. 11.2b). Planning based on experience is a feature of intelligence as defined above.

More generally, mechanistic mathematical models are powerful tools to study how initial conditions and system parameters affect observed dynamics. Such a *quantitative prediction of system behavior* is relevant in the context of many applications. Consider, for example, problems from epidemiology and vaccination strategy planning (STIKO, 2016). In clinical applications, it can be very helpful to estimate model parameters based on available patient data and to predict the future course of disease using the parameterized model (Stiehl et al., 2015, 2020; Kather et al., 2017, 2018). However, conclusions and predictions based on a model are only valid if the model assumptions are in agreement with reality. Whenever possible, the satisfaction of model assumptions has to be checked before applying a model to real world questions.

A desirable property of models is the so-called *robustness*. A robust model delivers a sufficiently accurate prediction even in cases where the underlying assumptions are only approximately satisfied. Coming back to the example of bacterial growth: if bacteria die but the mortality rate is small compared to the division rate, the exponential growth law still represents a good approximation of experimental observations; in this sense, the model is robust.

4.4 Model and Hypothesis Selection, Hypothesis Generation

A significant disagreement between model predictions and observations can contribute to the generation of new hypotheses. For example, long-term observations of bacterial cultures violate the exponential growth law. This mismatch suggests that an important process was not accounted for in the model. Possible biological mechanisms responsible for the mismatch are resource scarcity and toxic metabolic products which reduce division rates or induce cell death. A phenomenological model which accounts for this observation is the logistic growth model.

Often multiple models exist to describe and explain a given observation. In this case it is crucial to identify which of the given models is the best approximation of reality. *Model selection* is a systematic and statistically sound procedure to rank the performance of different models and rule out a subset of them based on available data *(*Burnham & Anderson*,* 2002*)* (Fig. 11.2c). The procedure of model selection is reminiscent of learning from experience: Based on the available data (i.e., experience), model selection is used to "learn" which model assumptions are not compatible with reality and which models lead to a satisfactory description of reality.

Model selection can be used to compare competing mechanistic hypotheses by formulating each hypothesis as a model and comparing the dynamics of the respective models with available data. Hypotheses that lead to models that closely approximate reality can then be tested experimentally. Based on this approach, mathematical modeling can generate hypotheses for experimental science. *Hypothesis generation* through modeling and simulation is increasingly used in the life sciences (Manesso et al., 2013; Stiehl et al., 2015, 2020; Kather et al., 2017, 2018; Kalamakis et al., 2019; Wang et al., 2017). In this way, mathematical models can contribute to the mechanistic understanding of complex issues. To comprehend complex phenomena is a characteristic feature of intelligence in the sense of the above definition.

4.5 Optimal Experimental Design

Different models can perform equally well when compared to data, especially in cases where available data only cover a narrow range of scenarios. Systematic model analysis and simulation can help to identify experimental conditions under which competing models, and thus competing hypotheses, lead to different dynamics (Fig. 11.2d). The respective experimental conditions can be used to discriminate between competing hypotheses. In this way, it becomes possible to disprove models and hypotheses through appropriately designed experiments. The use of mathematical and computational models to optimally design experiments is referred to as *optimal experimental design*. Another example for optimal experimental design is the identification of time points at which measurements have to be taken in order to estimate a given parameter with optimal accuracy. Optimal experimental design is an example of systematic planning that facilitates the achievement of a given goal (Kitsos, 2013). Such a capability is a characteristic feature of intelligence.

4.6 Data Analysis and Interpretation

Mechanistic models can facilitate the analysis and interpretation of complex data. Systematic model simulations can help to identify system properties ("patterns", "targets") that are characteristic for a given process of interest and that can be searched for in available datasets. In this sense models can guide *data analysis* by suggesting to researchers what to look for in large sets of data. Based on the "experience" of model simulation, patterns in data can be detected and explained. This is reminiscent of "quick learning" and "learning from experience." Both are characteristics of intelligence.

4.7 Complexity Reduction

Model reduction is the process of converting complex mechanistic models into simpler models which, under certain assumptions, show a very similar behavior (Banasiak & Lachowicz, 2014). C*omplexity reduction* not only simplifies the practical application of the respective model, it also helps to identify which mechanisms are required to give rise to specific phenomena and which mechanism can be neglected (Fig. 11.2e). Model reduction helps to identify the most important components of a system and in this way contributes to the understanding of complex phenomena as well as to their classification in the context of previous knowledge. Identification of essential processes, assignment of observations to underlying mechanisms, discarding of unnecessary information are characteristics of intelligence. Filtering out essential and discarding unnecessary information is a key ability of the brain and is possibly a prerequisite for survival in a complex environment (Cromwell et al., 2008).

5 Which Tools and Methods Are Used for Mechanistic Modeling?

Mechanistic modeling relies on a broad range of mathematical and computational approaches (Rutherford, 1995). Differential equations are particularly useful, as they allow relating the change of a variable (i.e., its derivative) to underlying processes. Differential equations containing only derivatives with respect to one variable are referred to as *ordinary differential equations.* They are used, e.g., when the temporal change of a variable is modeled. As soon as the temporal and spatial changes of a variable are relevant, *partial differential equations* can be used. Differential equations which incorporate random fluctuations are called *stochastic differential equations* (Daun et al., 2008). They also play a role in mechanistic modeling. A major advantage of using differential equations is that analytical methods can be used to systematically study and, in the best case, fully characterize the model dynamics. Differential equation models are ideal tools when a population consists of a large number of similar individuals. In a certain sense, they describe average quantities. Such models are usually formulated in units of concentration or density. So-called individual-based models describe the dynamics of a population from the perspective of its individual units (e.g., single cells, single molecules, single people) which act based on a predefined set of rules (Breckling, 2002). In this type of model, the individuals may act very differently from each other. This approach is ideally suited to account for stochastic effects in small populations. Individual-based models are usually not tractable by systematic mathematical analysis and must be simulated on a computer. Characterization of their dynamics is often challenging due to the required computation times and the large number of involved parameters. Computational methods are also required for the analysis of complex differential equation models. In this case numerical methods are used to approximate the solution of the respective differential equations. Efficient numerical algorithms for this task are developed at the interface of mathematics and computer sciences. Methods from statistics and optimization are used for model selection and parameter estimation.

6 Examples of Mechanistic Mathematical Modeling in Current Research

In the following, we will outline two examples of mechanistic modeling from our current research. This illustrates how mathematical modeling can contribute to the understanding of biomedical problems.

6.1 Example 1: Aging of Neural Stem Cells

The lifelong formation of neurons (neurogenesis) is essential for the cognitive function of the brain. During neurogenesis, neurons are generated in a multi-step process from so-called neural stem cells. The existence of neural stem cells has been demonstrated at two main localizations of the adult mouse brain. These are the hippocampus and the subventricular zone. Measurements show that the number of neural stem cells decreases with increasing age. However, the rate at which the stem cell population declines reduces with increasing age. This suggests a mechanism to counteract the depletion of neural stem cells at old age. The mechanisms underlying this phenomenon are the subject of current research.

Neural stem cells are mostly dormant (quiescent) cells. When a neural stem cell is activated, it divides into two progeny. The so-called self-renewal probability indicates the probability with which each of the daughter cells is a stem cell. Three scenarios can be distinguished: either both daughter cells are neural stem cells or both daughter cells are so-called progenitor cells, i.e., more mature compared to their parent cell, or one daughter cell is a stem cell and one is a progenitor cell. Stem cells that emerge from division reenter the quiescent state. Experimental data demonstrate that the proportion of active neural stem cell decreases with age. The question of whether these observations are related to changes of stem cell properties is still open.

Various scenarios are intuitively plausible to explain the observations, e.g., a delayed division of activated cells, a change in the probability of self-renewal or a lower activation probability at high ages. Due to experimental limitations it is not possible to observe individual stem cells over time *in vivo*. We use model selection to investigate the question of whether, and if so how, neural stem cells change with aging. For this purpose, different mathematical models are designed. The first model assumes that all stem cell parameters are constant in time (i.e., activation probability, self-renewal probability, and the time interval between activation and division). The second model is based on the assumption that the interval between activation and cell division is age-dependent. The third model assumes that the self-renewal probability increases with age, and the fourth model assumes that the probability of activation decreases with age.

Model selection suggests that the model assuming reduced activation probability fits the experimental data best (see Fig. 11.3) (Kalamakis et al., 2019). This result implies that the age-related reduction of activation probability could be a biological mechanism to slow down the depletion of the stem cell population. Of all the models considered, this is the only mechanism that can explain both the time evolution of the total stem cell number and the altered proportion of active stem cells. Gene

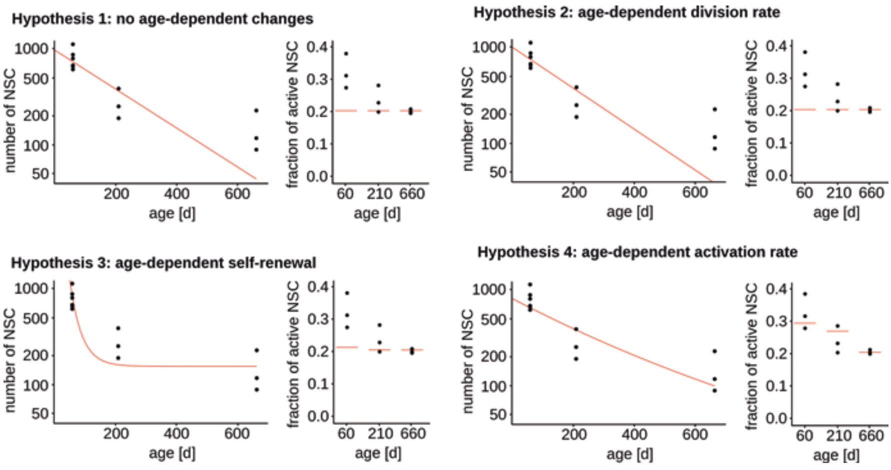

Fig. 11.3 Model selection applied to questions of adult neurogenesis. Models based on different assumptions are compared with experimental data (shown as black dots). The best fitting model assumes that the activation rate of quiescent neural stem cells decreases with age. This mechanism is supported by experimental findings. (Source: Figure adapted from Kalamakis et al. (2019))

expression studies and knockout experiments confirm this view (Kalamakis et al., 2019).

This example demonstrates how the combination of mathematical models and data can provide insight into biological mechanisms. Based on the underlying mechanistic assumptions and the experimental data, model selection infers which mechanistic hypotheses fit the data and which hypotheses are contradictory to the data. Phrased differently, model selection makes logical decisions based on data and hypotheses. Because of the complicated dynamics of each model, this decision is beyond intuitive understanding. This example shows the interaction between human intelligence, which manifests itself in the formulation of mechanistic hypotheses and the selection of suitable experiments, and mathematical intelligence, which draws logical conclusions from these ingredients.

6.2 Example 2: Impact of Leukemic Stem Cell Properties on Disease Progression

Acute myeloid leukemia is one of the most aggressive malignant diseases. It affects the hematopoietic (blood forming) system. During disease progression, mutated cells with a specific morphology, referred to as blasts, accumulate in the bone marrow and impair healthy blood cell formation. The blasts are derived from leukemic stem cells (cancer stem cells). Cancer stem cells are characterized by their ability to divide infinitely often and to maintain their population throughout the course of the disease. Leukemic stem cells give rise to leukemic progenitor cells, which in turn form blasts. Unlike leukemic stem cells, leukemic progenitor cells and blasts can only undergo a limited number of divisions. Therefore, the disease could be cured by eradication of the leukemic stem cell population. For this reason, leukemic stem cells are the focus of clinical research. Healthy blood formation is maintained by a stem cell population known as hematopoietic (blood-forming) stem cells.

Recent research demonstrates that stem cells require a specific microenvironment to maintain their function. This microenvironment is referred to as the stem cell niche. There is evidence that leukemic stem cells dislodge hematopoietic stem cells from the niche. Human bone marrow is inaccessible for time-resolved *in vivo* observations of single cells. Therefore, we have designed mathematical models to investigate how the properties of leukemic stem cells impact on disease progression. The mathematical models suggest that hematopoietic and leukemic stem cells compete for spaces in a joined niche and that hematopoietic stem cells are out-competed by their malignant counterparts (Wang et al., 2017). This triggers a decline of the hematopoietic stem cell population that is followed by an impairment of healthy blood cell formation. Furthermore, model simulations identify which leukemic stem cell properties significantly impact on the speed of disease progression (Stiehl et al., 2020; Wang et al., 2017). According to the model, not only the division rate of leukemic stem cells plays an important role but also the probability with which a leukemic stem cell arising from division displaces a hematopoietic stem cell from the niche (Stiehl et al., 2020). The model suggests a nonlinear relation between these two cell properties and the speed of disease progression.

Based on simultaneous measurements of the hematopoietic stem cell count and the blast frequency at the time of initial diagnosis, a model-based quantification of leukemic stem cell properties is possible. The model-based quantification of these cell parameters could provide additional information compared to the established clinical risk-scoring. Development and application of a model-based risk-stratification to the patient cohort from a clinical trial confirms that clinical risk-stratification could be improved using the model (Fig. 11.4) (Stiehl et al., 2020).

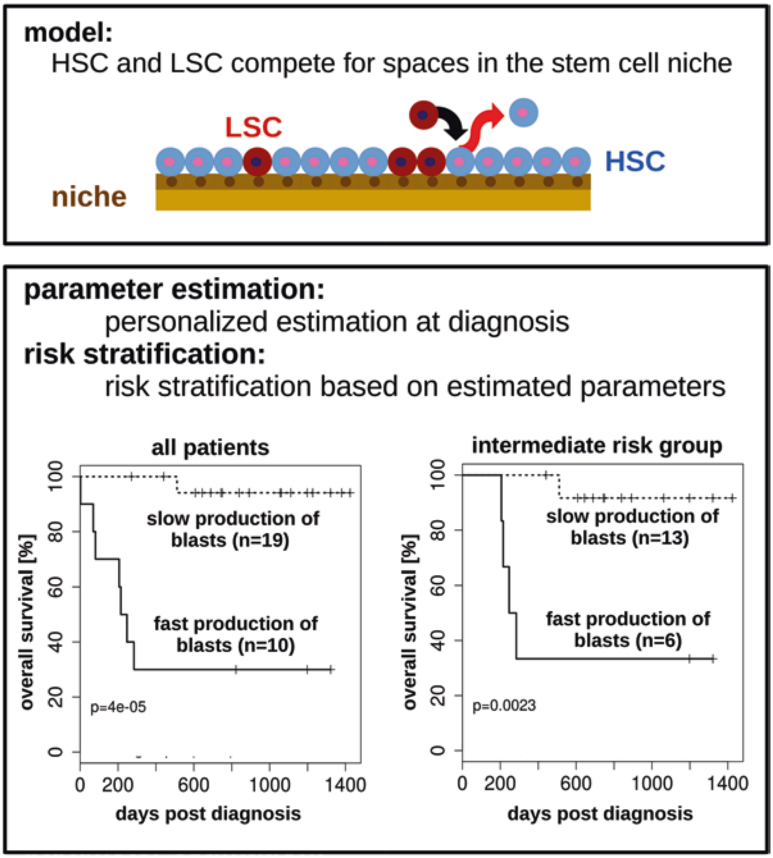

Fig. 11.4 Parameter estimation and simulations applied to questions of personalized medicine. Based on a model that describes the competition of hematopoietic stem cells (HSC) and leukemic stem cells (LSC) for spaces in the stem cell niche, important determinants of disease progression are identified. Based on data available at the time of diagnosis, model parameters are estimated. The estimated parameters allow assigning patients to different risk groups. Using this procedure, patients belonging to the genetically defined intermediate risk group can be subdivided into two groups with significantly different prognosis. (Source: Figure adapted from Stiehl et al. (2020))

This example shows that mechanistic models can provide insight into the progression of malignant diseases and that they may help to improve risk-scoring. Due to the complex and nonlinear processes underlying disease progression, model-based risk classification provides more information than clinical classification, which is based on analogy considerations, intuitive arguments, and empirical experience.

In this example, mathematical methods help to identify relevant process parameters and to quantify them using data of individual patients. This leads to a computer-based machinery that assigns patients to different prognosis groups. This approach illustrates how mathematical intelligence can help to make decisions (group assignments) and predictions (prognosis). The contribution of human intelligence to this procedure lies in the formulation of the model assumptions and in the identification of measurable quantities, such as cell surface markers, which can be used for individualized parameter estimation.

7 Data-Driven Processes

Mechanistic models are a powerful tool to study the impacts of a hypothetical mechanism on observable variables and to clarify whether it is sufficient to explain available data. Therefore, mechanistic modeling is also referred to as a *hypothesis-driven* approach. In contrast to hypothesis-driven approaches, which rely on mechanistic hypotheses, data-driven approaches aim to derive classifications (i.e., to answer questions), directly from available data. Machine learning is an important example of the data-driven approaches.

In the simplest case, so-called supervised learning, the answer to the posed question is known for the training data. The algorithm attempts to extract features from the training data that allow correctly answering the question of interest. To this end, approaches from statistics and optimization can be used (Ertel, 2017). If the trained algorithm is applied to data that was not used for training, it attempts to answer the posed question for the new data set by extracting and analyzing the features identified during the training. This approach technically implements learning from experience: based on the experience within the training data, the algorithm classifies new, unknown data.

Data-driven methods are particularly promising when a hypothesis-driven approach is out of reach. This is the case when there is too little knowledge about the underlying processes or when the underlying processes are too complex to be modeled in a meaningful mechanistic way. An advantage of many data-driven methods is that they can be applied "out-of-the-box" without having to consider complex hypotheses beforehand.

In many cases, data-driven methods require relatively large sets of training data compared to mechanistic modeling. This is partly due to the fact that the algorithm lacks knowledge about possible mechanisms and all information must be extracted directly from data. This can naturally lead to problems when a training dataset is not chosen to be representative or does not cover the entire space of occurring possibilities. Data-driven methods find a very wide application in image processing and medical image analysis.

8 Outlook

Current research aims to join hypothesis-driven and data-driven approaches. There is hope that this strategy results in a synergy of the strengths of both model types. Various approaches exist to accomplish this. For example, it is possible to model well-understood processes mechanistically and to include less well characterized factors using a data-driven approach. In this context, it is an interesting question whether mechanistic models can be used to generate training data for data-driven models. This could for example be used for model selection: A learning algorithm could be trained with data generated by different models and then help to identify which of the different models best fits experimental data. In life sciences mechanistic models are important tools to predict individual disease progression. However, different validated models which are equally powerful when applied to large patient cohorts may lead to diverging predictions for a given individual. In this case, it is necessary to identify the model that is most appropriate for the given patient. Data-driven approaches can possibly help to solve this problem by making use of individual patient characteristics, which are so far not included in the mechanistic models.

9 Conclusion

Mechanistic models are problem-specific approximations of reality. Their level of complexity is tractable by mathematical and computational methods. Even though models are simplifications, they fit sufficiently well to certain aspects of reality such that they prove to be useful in research and application. Mechanistic models allow understanding how the quantitative and qualitative dynamics of a system depend on model assumptions, initial conditions, and process parameters. If the model assumptions are sufficiently realistic, mechanistic models can be used to quantify important process parameters based on available data. If all important process parameters are known, mechanistic models can quantitatively predict the time evolution of a system. Disagreement between model and reality indicates gaps in our understanding and leads to new hypotheses.

Mathematical and computational models have properties that are often considered as characteristic features of intelligence. These include the capability to predict events, to draw conclusions based on experience, to make knowledge-based decisions, to solve problems and to strategically plan procedures (e.g., experiments). Mechanistic models help to reduce a complex problem to key processes, to relate mechanisms to observable phenomena, or to choose one out of multiple competing hypotheses. The combination of mechanistic models with data-driven methods can help to include phenomena still lacking a mechanistic understanding.

Mathematical models and trained algorithms are designed to solve specific problems. Both can lead to questionable predictions. This problem arises for example if model assumptions are violated or if they are trained based on invalid (e.g., not representative) data. Human intelligence is more flexible compared to mathematical or algorithmic constructs. Nevertheless, human intelligence sometimes also draws invalid conclusions. Pareidolia and optical illusions are two examples for this. Mathematical, machine, and human intelligence deal with a complex environment under the constraint of limited resources. This inevitably requires strategies to reduce complexity and may lead to the tendency to falsely identify new observations with known patterns.

References

Banasiak, J., & Lachowicz, M. (2014). *Methods of small parameter in mathematical biology*. Birkhäuser.

Boring, E. G. (1923). Intelligence as the tests test it. *New Republic, 36*, 35–37.

Breckling, B. (2002). Individual-based modelling: Potentials and limitations. *ScientificWorldJournal, 2*, 1044–1062.

Burnham, K. P., & Anderson, D. R. (2002). *Model selection and multimodel inference: A practical information-theoretic approach*. Springer.

Cromwell, H. C., Mears, R. P., Wan, L., & Boutros, N. N. (2008). Sensory gating: A translational effort from basic to clinical science. *Clinical EEG and Neuroscience, 39*(2), 69–72.

Daun, S., Rubin, J., Vodovotz, Y., & Clermont, G. (2008). Equation-based models of dynamic biological systems. *Journal of Critical Care, 23*(4), 585–594.

Ertel, W. (2017). *Introduction to artificial intelligence* (2nd ed.). Springer.

Gerrig, R. J. (2013). *Psychology and life* (20th ed., p. 243). Pearson.

Gottfredson, L. S. (1997). Mainstream science on intelligence. *Intelligence, 24*(1), 13–23.

Hiscock, T. W., & Megason, S. G. (2015). Mathematically guided approaches to distinguish models of periodic patterning. *Development, 142*(3), 409–419.

Kalamakis, G., Brüne, D., Ravichandran, S., Bolz, J., Fan, W., Ziebell, F., Stiehl, T., Catalá-Martinez, F., Kupke, J., Zhao, S., Llorens-Bobadilla, E., Bauer, K., Limpert, S., Berger, B., Christen, U., Schmezer, P., Mallm, J. P., Berninger, B., Anders, S., … Martin-Villalba, A. (2019). Quiescence modulates stem cell maintenance and regenerative capacity in the aging brain. *Cell, 176*(6), 1407–1419.e14.

Kather, J. N., Poleszczuk, J., Suarez-Carmona, M., Krisam, J., Charoentong, P., Valous, N. A., Weis, C. A., Tavernar, L., Leiss, F., Herpel, E., Klupp, F., Ulrich, A., Schneider, M., Marx, A., Jäger, D., & Halama, N. (2017). In silico modeling of immunotherapy and stroma-targeting therapies in human colorectal cancer. *Cancer Research, 77*(22), 6442–6452.

Kather, J. N., Charoentong, P., Suarez-Carmona, M., Herpel, E., Klupp, F., Ulrich, A., Schneider, M., Zoernig, I., Luedde, T., Jaeger, D., Poleszczuk, J., & Halama, N. (2018). High-throughput screening of combinatorial immunotherapies with patient-specific in silico models of metastatic colorectal cancer. *Cancer Research, 78*(17), 5155–5163.

Kitsos, C. P. (2013). *Optimal experimental design for non-linear models - Theory and applications*. Springer.

Manesso, E., Teles, J., Bryder, D., & Peterson, C. (2013). Dynamical modelling of haematopoiesis: An integrated view over the system in homeostasis and under perturbation. *Journal of the Royal Society. Interface., 10*(80), 20120817.

Marciniak-Czochra, A., Stiehl, T., Ho, A. D., Jäger, W., & Wagner, W. (2009). Modeling of asymmetric cell division in hematopoietic stem cells--Regulation of self-renewal is essential for efficient repopulation. *Stem Cells and Development, 18*(3), 377–385.

Mercker, M., Lengfeld, T., Höger, S., Tursch, A., Lommel, M., Holstein, T. W., & Marciniak-Czochra, A. (2021a). β-Catenin and canonical Wnts control two separate pattern formation systems in Hydra: Insights from mathematical modelling. *BioRxiv*. https://doi.org/10.1101/2021.02.05.429954

Plante, T. G. (2005). *Contemporary clinical psychology* (2nd ed., p. 215). Wiley.

Wechsler, D. (2008). *Wechsler Adult Intelligence Scale* (4th ed.). Pearson.

Østby, I., Rusten, L. S., Kvalheim, G., & Grøttum, P. (2003). A mathematical model for reconstitution of granulopoiesis after high dose chemotherapy with autologous stem cell transplantation. *Journal of Mathematical Biology, 47*(2), 101–136.

Stiehl, T., Ho, A. D., & Marciniak-Czochra, A. (2014). The impact of CD34+ cell dose on engraftment after SCTs: Personalized estimates based on mathematical modeling. *Bone Marrow Transplantation, 49*(1), 30–37.

Turing, A. (1952). The chemical basis of morphogenesis. *Philosophical Transactions of the Royal Society of London B, 237*(641), 37–72.

Stiehl, T., Wang, W., Lutz, C., & Marciniak-Czochra, A. (2020). Mathematical modeling provides evidence for niche competition in human AML and serves as a tool to improve risk stratification. *Cancer Research, 80*(18), 3983–3992.

Stiehl, T., Baran, N., Ho, A. D., & Marciniak-Czochra, A. (2015). Cell division patterns in acute myeloid leukemia stem-like cells determine clinical course: A model to predict patient survival. *Cancer Research, 75*(6), 940–949.

Ravichandran, S., & Del Sol, A. (2017). Identifying niche-mediated regulatory factors of stem cell phenotypic state: A systems biology approach. *FEBS Letters, 591*(3), 560–569.

Shankland, R. S. (1964). Michelson-Morley experiment. *American Journal of Physics, 32*, 16–35.

Nieman, R. E., Fisher, D. G., & Seborg, D. E. (1971). A review of process identification and parameter estimation techniques. *International Journal of Control, 13*(2), 209–264.

STIKO. (2016). *Modelling methods for predicting epidemiological and health economic effects of vaccinations – Guidance for analyses* to be presented to the German Standing Committee on Vaccination (STIKO).

Wang, W., Stiehl, T., Raffel, S., Hoang, V. T., Hoffmann, I., Poisa-Beiro, L., Saeed, B. R., Blume, R., Manta, L., Eckstein, V., Bochtler, T., Wuchter, P., Essers, M., Jauch, A., Trumpp, A., Marciniak-Czochra, A., Ho, A. D., & Lutz, C. (2017). Reduced hematopoietic stem cell frequency predicts outcome in acute myeloid leukemia. *Haematologica, 102*(9), 1567–1577.

Rutherford, A. (1995). *Mathematical modelling techniques, Dover Books on computer science*. Dover Books.

Thomas Stiehl studied mathematics and medicine at Heidelberg University, where he also received his PhD in mathematics. Since 2021, he has been Professor for "Disease Modeling" at the University Hospital Aachen and RWTH Aachen University. His research is devoted to mechanistic mathematical and computational modeling of stem cell-driven processes, e.g., in tissue regeneration and cancer. Thomas Stiehl's focus is the modeling of malignant diseases of the hematopoietic system, such as acute myeloid leukemia. His work covers aspects of personalized and systems medicine. It is characterized by a close link to clinical questions and the application of models to routine data. Other research topics include adult neurogenesis, the regulation of plant stem cells and questions related to stem cell aging.

Anna Marciniak-Czochra is Professor of Applied Mathematics at Heidelberg University and head of the research group "Applied Analysis and Modeling in Biosciences" at the Institute of Applied Mathematics, IWR and Bioquant. She studied mathematics at Warsaw University, Poland, and received her PhD in Heidelberg. Anna Marciniak-Czochra's interdisciplinary expertise is in applied mathematics, biomathematics, and systems biology. Her research focuses on the dynamics of self-organization and structure formation in development, regeneration, and cancer. The goal of her research is the development and analysis of multiscale mathematical models for the dynamics of structure formation in multicellular systems. Her mathematical focus is on partial differential equations, dynamical systems, and multiscale analysis. The mathematical models and methods developed in Anna Marciniak-Czochra's group are applied to problems in developmental and cell biology as well as medicine in collaboration with experimentalists and medical doctors.

Chapter 12
Artificial Intelligence and Algorithms: True Progress or Just Digital Alchemy?

Vincent Heuveline and Viola Stiefel

Abstract From chess computers to self-driving cars to the great science fiction successes in the media field—AI is omnipresent today. Starting from the question of the interaction between human and machine, this article first deals with the distinction between strong AI, which is primarily at home in the cinematic world, and weak AI, under which all actual AI systems fall today. The aspect of learning and the role of algorithms here are of eminent importance for the research and further development of the AI systems that exist to date. On the basis of artificial neural networks, computers learn, for example, to distinguish between images of cats and dogs. But can the AI also be given more weighty decisions? And how does the algorithm make a decision, mathematically speaking? What happens if the data the computer learns with is error-prone? The consequences of these considerations undoubtedly open up a range of new issues that are not exclusively relevant for research, but for society as a whole, and which will become increasingly central with the growing use of AI.

1 Introduction

Not infrequently, the question is raised how it can be that a computer generates new knowledge that the programmer did not intend at all and which is completely unknown to him. One should actually be able to assume that the computer slavishly executes the sequence of binary commands and instructions that the programmer defined by means of his software development. The computer does not make mistakes. At most, they occur when the software developer has overlooked a few of the famous bugs in his software, causing the machine to behave erroneously or even erratically. In this style, the relationship between human and machine is clearly

V. Heuveline (✉)
IWR - Engineering Mathematics and Computing Lab (EMCL), University of Heidelberg, Heidelberg, Germany
e-mail: vincent.heuveline@uni-heidelberg.de

V. Stiefel
University Computing Center, University of Heidelberg, Heidelberg, Germany
e-mail: viola.stiefel@urz.uni-heidelberg.de

R. M. Holm-Hadulla et al. (eds.), *Intelligence - Theories and Applications*,
https://doi.org/10.1007/978-3-031-04198-3_12

defined: the human dictates the tasks that the machine has to implement. The computer, as the executing instrument, does not critically weigh its reaction and does not show any feelings such as boredom, even if the tasks to be performed consist of repetitive, tedious steps. The tasks are expected to be performed deterministically and reproducibly. The power supply ensures that the bytes and bits always flow in an orderly fashion and according to plan within the electronic circuits. In this context, there is little room for the machine to solve unexpected or even creative tasks. Humans thus think they are always in complete control of the machine. However, this widely held view is very deceptive. For example, a navigation system can calculate the shortest route between the city of Heidelberg and the wonderful medieval town of Bad Wimpfen. However, we cannot assume that the developer of the navigation system knows all the insider tips of the explored area—in our case Heidelberg—and decisively designs routes and plans for it. Rather, the programmer will implement a procedure—generally in the sense of a mathematical algorithm—that is capable of calculating the shortest path between two points on a map. The question that arises here is whether the programmer still has control over their software. What does it mean to have control over an algorithm? Can unexpected results arise that were not initially intended? Can an algorithm, when combined with data, generate knowledge—in this case, the shortest or fastest path—that the programmer was not aware of in the first place? In this chapter, we will address, step by step, these fundamental questions, which are of an essential nature for understanding and evaluating AI. In the process, we will discover that the relationship between human and machine in this context is more subtle than initially assumed.

2 Strong Versus Weak AI

The list of science fiction authors and filmmakers who have devoted their works to the subject of AI is extremely long and varied. One almost constant in these books and films is that the AI portrayed is at least equal to human abilities in virtually all areas, if not surpassing them. The above-average reasoning ability of Commander Data from the science fiction series Star Trek, combined with his seamless encyclopedic knowledge in the sense of Big Data, makes him a fascinating character who surpasses human intelligence in almost every area. The ability to communicate in all natural known languages, inherent in the humanoid character C3PO from the movie Star Wars, is no less impressive. To humans, this cognitive superiority may seem at least respect-inspiring, at times even frightening. Stephen Hawking, for example, has always warned of the dangers posed to humanity by artificial intelligence. The ubiquitous media portrayal of AI only contributes to a limited extent to calming and defusing the situation. James Cameron, for example, sets further accents in connection with artificial intelligence in the second film of his well-known film series Terminator with the cyborg of the same name: Terminator combines the superlatives of all human abilities to achieve an overriding goal: to save mankind. In the process, Terminator even understands and masters a skill that is considered an exclusively human attribute—humor. All these characters have in common that they represent the expression of a so-called strong artificial intelligence, which encompasses all sides of human intelligence—also and especially in the combination of the different abilities (Flowers, 2019; Liu, 2021).

The quest for superhuman abilities, superpowers, and hyperintelligence has fascinated mankind since time immemorial, and for this reason is reflected not least in all forms of media. An example from Greek mythology would be Icarus, who ultimately failed because he wanted to reach too high. It remains to be seen to what extent the same fate threatens today's efforts of mankind to make itself godlike through a strong AI (think of Harari's Homo Deus) (Fjelland, 2020). At present, however, it can be stated that existing technology is far from enabling strong artificial intelligence as a reality. Today's AI systems fall under the category of weak AI ("weak artifical intelligence") (Walch, 2019): human intelligence or human cognitive abilities are only matched and possibly surpassed in delimited sub-areas. Image and speech recognition, automated translation, and self-driving cars are just a few examples of where (weak) artificial intelligence is used productively today.

3 Weak AI Is Mathematics

The Dartmouth Conference ("Dartmouth Summer Research Project on Artifical Intelligence"), which took place in 1956 at Dartmouth College in Hanover, New Hampshire (USA), is considered the beginning of the study of artificial intelligence in the sense of the concepts and approaches we use today.

The name "Artifical Intelligence" comes from the initiator of the conference, John McCarthy. In the context of this conference, Marvin Minsky, Claude Shannon, John von Neumann, and Ray Solomonoff should also be mentioned, who have had a very strong influence on the further developments of AI. A close examination of both the topics covered and the expertise represented makes it very clear that the underlying AI concepts are grounded in mathematical abstractions (Shaffi, 2020; Garrido, 2010). In the context of this spirit of optimism, the closing words of the conference seem on the one hand promising, but on the other hand still cautiously non-committal: "[…] every aspect of learning or any other feature of intelligence can in principle be so precisely described that a machine can be made to simulate it" (https://250.dartmouth.edu/highlights/artificial-intelligence-ai-coined-dartmouth). An important insight for the past decades from this conclusion and from the whole conference is that a computer can perform more than just the core task of scientific computing—classical numerical simulation. A computer is indeed capable of learning using appropriate algorithms. However, experience shows that this can generally only be accomplished if one has significant computing power and training data (Deisenroth et al., 2020). Moreover, the past decades have shown that developments in computer technology have acted as a catalyst for AI development.

Moore's Law, which is actually more of an observation, states that every 18 months there is a doubling of the available computing power. This rule of thumb, which has not been disproved to date, corresponds to exponential growth. Such huge technological developments are undoubtedly crucial to the long-celebrated successes of AI in the game of chess and Go. Supercomputers and high-performance computers, which are heavily used for AI, have now become symbols of the greatest possible computing power available. The number of floating point operations per second, or FLOPS, is a measure of a computer's performance. Today, the fastest supercomputers are capable of computing around 500 PetaFLOPS (Peta = 10^{15}). This corresponds approximately to 500,000,000,000 operations per second.

Even for experts, such orders of magnitude are challenging and difficult to grasp. This concentrated computing power is a necessary but not sufficient condition for the successful use of AI. The learning procedures required in AI are based on training data, on the basis of which the computer is able to learn facts. In general, the more precise and comprehensive this data is, the better the computer can learn. A classic example of this in textbooks is distinguishing between cats and dogs on the basis of images. The computer is trained to "learn" with the help of a large number of pictures of cats and dogs. When a completely new image is presented to the computer, it is then able to distinguish whether it is a cat or a dog. The trick is that it is irrelevant whether the computer knows the exact breed of dog or cat presented. Like a human being, the computer has learned characteristics with the help of the training data, on the basis of which it can distinguish the animals—almost always correctly. It is essential that the distinguishing features have not been explicitly programmed in advance, but are automatically defined by the computer via the corresponding AI algorithms.

Experience shows that the quality and quantity of the training data are crucial in this respect. This is where technological IT developments play a crucial role. In an era of ubiquitous digital communication, but also of networking, e.g., via the Internet of Things (IoT), digital data is produced in a number of constellations. The term "Big Data" is self-evident in this respect: in several application areas, considerable amounts of structured and unstructured data are produced. It is not the data as such that is important, but the possibility of generating knowledge and insights from this data. Many AI systems thrive on the presence of such data and are thus able to extract important and new insights from it (Sun & Wang, 2017). In this context, it is significant that the amount of data has become so extensive in some cases that a single human would not be able to analyze this data without computer support, sometimes using AI-based approaches. Are humans thus losing control over their decision-making? How reliable are AI systems really? An answer to these questions requires a closer look into how AI algorithms work.

4 Algorithms for AI

The use of AI presupposes that the computer used has the ability to learn. A first—but erroneous—thought would be to transfer the responsibility of explicit learning to the programmer of the computer. The programmer, as the "chief pedagogue" of the machine, can prescribe rules and instructions for action via the developed software, according to which pattern the machine has to react in given situations. A major disadvantage of such an approach would be that the programmer himself would have to have the required knowledge in order to be able to transfer it to the appropriate software. Consequently, the programmer of the Go game would have to know all the tips and tricks of the Go game and implement them explicitly. Conceptually, this would mean that the existing knowledge of the machine would always be bound to the skills of the programmer team and thus de facto be considerably limited. Such a machine would hardly be able to defeat the world's best Go players. However, the successes of the Alpha-Go software against the Go champions of this world have provided proof to the contrary. The machine has always been able to win the ancient Chinese game of Go with clear superiority. How is that even possible?

The real trick is to teach the machine how to learn for itself, more or less according to the principle of help for self-help. The programmer remains the "chief educator" of the machine. However, they do not try to teach the machine the content that they generally neither know nor have mastered. Rather, they convey a methodology for how the machine can learn for itself. Such approaches fall under the term "machine learning": The idea is to artificially generate knowledge from digital data that enables the machine to make decisions on its own (Thesing et al., 2019). The practical implementation of such approaches is carried out with the help of algorithms developed specifically for this purpose. These algorithms can be roughly divided into two categories: supervised learning and unsupervised learning (Brownlee, 2019; Radford et al., 2015). The exact description of these different groups is beyond the scope of this paper. Accordingly, we will focus exclusively on the algorithms of the supervised learning category in the following.

In supervised learning, the computer learns from given pairs of inputs and outputs. For example, an image with a cat (input) is associated with a value of 0 (output) and an image with a dog (input) is associated with a value of 1 (output). The trick is to define a mapping or function between the inputs and outputs in such a way that even unknown images are correctly classified according to the above principle. For the definition of such mappings, the use of so-called neural networks has proven very useful (Saxton et al., 2019; Yosinki et al., 2014).

In biology, neural networks refer to structures of the brain of animals and humans. Neurons form an extremely complex network—in the human cerebral cortex 10 billion neurons work in fine coordination. Each neuron is connected with about 2000 other neurons. The ability to learn is achieved by changing the connection strengths of the existing neurons. Thus, information is not stored in individual neurons, but is represented by the entire state of the neural network with all connection strengths. In the field of AI, people use artificial neural networks which are strongly inspired by their biological counterpart (Nikolic, 2017). However, artificial neural networks are concerned with obtaining an abstraction in terms of model building, which can be used to define the mapping between inputs and outputs in the best possible way. The learning process based on such artificial neural networks consists in determining weights along the connections (edges) of a graph for which the neurons act as nodes. The pairs of inputs/outputs as training data are used to determine these weights. Mathematically, this is a model calibration in the sense of parameter identification. Here, the weights along the edges of the neural network are the parameters to be identified: the learning process as a parameter identification problem.

It should not go unmentioned that, from a mathematical point of view, there are still a number of open questions concerning the properties of such neural networks. For example, the determination of the dimensioning of such a neural network for a given application is still a challenge, which generally has to be defined empirically via numerous tests. Some digital alchemy is always necessary here. For simple neural networks, one can prove that the underlying methodology corresponds to known procedures from the field of numerical optimization. Thus, for such methods, one has the decidedly important support of mathematics, which provides a foundation for both the understanding and convergence statements of the methods. Unfortunately, for many procedures that have proven themselves in practice, there is little mathematical insight into why these procedures work and whether this is indeed always the case. This explains why this technology is repeatedly referred to as a black box model. For the use of AI in critical areas, such a situation may hold some dangers. For example, how sensitive is the neural network to erroneous data? There is still a very great need for research here so that such approaches are not confirmed by empiricism alone.

5 AI as a Black Box

In specific sub-areas, AI already surpasses human cognitive abilities. Quantities of training data are processed that a human brain could neither store nor process in an entire lifetime. As impressive as such results are, the question arises whether important or even critical decisions can be made at all on the basis of such results.

5.1 Can AI Technology Be Fundamentally Trusted to Make Important Decisions?

This question, which is often avoided in such clarity due to the celebrated successes of AI, is actually of significant importance. The terse statement that computers don't make mistakes no longer applies in these areas. For many applications, no one—not even the programmer who wrote the AI software—knows how the algorithm made its decision in the first place. This phenomenon is called the black box problem (Bleicher, 2017). In practice, modern learning algorithms seem to work for the most part. However, the fact is that these mechanisms that lead to a decision on the part of the AI are often simply not understood. In human/machine interaction, this is certainly an unprecedented paradigm shift. From a social perspective, this challenge also raises further questions:

- Who owns and understands the training algorithms or software?
- Who owns and understands the trained neural networks or AI models?

Knowing well that AI technology has reached quite a few areas of daily life, such foci are not only socially relevant but also of political importance (Ntoutsi et al., 2020; Mehrabi et al., 2019).

Assuming that AI algorithms learn optimally in a given metric, which—as of today—we cannot prove mathematically, the question remains whether the training data is at all suitable for the targeted decisions. In this context, several aspects have to be considered. In many application areas, the data originate from measurements that cannot be determined exactly in general. Measurement errors are commonplace for sensors. This now raises the question of how an AI system responds to both training and input data that may not be entirely error-free. The issue of the sensitivity of such systems with respect to fuzziness in the data is still a subject of research and has generally not been properly penetrated to date (Lim, 2020; Angwin & Larson, 2016).

Another aspect is possibly even more serious: What happens if the training data is incomplete and the AI system can only partially learn the data space? The danger of pre-programmed discrimination lurks precisely at this point. The magazine Focus of 12.10.2018 (Amazon, 2018) brought this issue to the point using the example of AI-based job application evaluations: “Artificial intelligence considers applications from women to be inferior.” After (human) analysis of the entire process, it was found that the training data was predominantly from males. Thus, the AI system made an assessment based on ignorance rather than objective consideration. Unfortunately, this is not a marginal issue, but a challenge that must always be illuminated: Constant and transparent scrutiny of AI systems with regard to possible discrimination/bias is certainly a key task not only for academia but also for all core stakeholders in society (Yapo & Weiss, 2018; O’neil, 2016; Fu et al., 2020; Baer, 2019).

6 Interpretable AI as a Possible Solution

With the increasing use of AI, the question of the interpretability and explainability of AI decisions has become essential. In English, the term “Explainable Artificial Intelligence (XAI)” describes the field that aims to make artificial intelligence explainable (Arrieta et al., 2020; Linardatos et al., 2021). This involves understanding how and why decisions have been made by AI systems. The black box character of many AI systems should thus be broken (Molnar et al., 2020). Scientifically, such questions still pose a great challenge. In the case of multi-layer DeepLearning models, for example, these aspects cannot be answered based on current scientific knowledge. In the past decade, innovative concepts have emerged that open up new perspectives in this context. A distinction is made between ante-hoc and post-hoc approaches (Escalante et al., 2018; Samek et al., 2019; Rudin, 2019). The ante hoc methodology focuses on models that are per se and a priori—i.e., beforehand—interpretable. The post hoc approach investigates the extent to which black-box models can be analyzed interpretably a posteriori. These topics are still the subject of research in many application areas.

In interpersonal interaction, we cannot always explain why fellow human beings make one decision or another. Our trust that a decision is correct or not is based on a variety of factors that we have already learned in childhood in our interactions with other people. In this context, trusting an algorithm that one may not understand correctly naturally protrudes very far from the usual range of human experience. Thus, the tension between true progress and digital alchemy to which AI is subject can only be resolved if courageous, transparent, and innovative paths continue to be taken.

References

Angwin, J., & Larson, J. (2016). *Machine bias*. Retrieved from https://www.propublica.org/article/machine-bias-risk-assessments-in-criminal-sentencing

Arrieta, A. B., et al. (2020). Explainable Artificial Intelligence (XAI): Concepts, taxonomies, opportunities and challenges towards responsible AI. *Information Fusion, 58*, 82.

Baer, T. (2019). *Understand, manage, and prevent algorithmic bias: A guide for business users and data scientists*. Apress.

Bleicher, A. (2017). *Demystifying the Black Box that is AI*. Retrieved from https://www.scientificamerican.com/article/demystifying-the-black-box-that-is-ai/

Brownlee, J. (2019). *A tour of machine learning algorithms*. Retrieved from https://machinelearningmastery.com/a-tour-of-machine-learning-algorithms/

Deisenroth, A., Faisal, A., & Soon, O. C. (2020). *Mathematics for machine learning*. Cambridge University Press.

Escalante, H. J., et al. (2018). *Explainable and interpretable models in computer vision and machine learning*. Springer.

Fjelland, R. (2020). Why generalized artificial intelligence will not be realized. *Humanities and Social Sciences Communications, 7*, 10.

Flowers, J. (2019). Strong and weak AI - Deweyan considerations. In *AAAI Spring Symposium*.

Fu, R., Huang, Y., & Singh, P. V. (2020). Artificial Intelligence and Algorithmic Bias: Source, Detection, Mitigation, and Implications. INFORMS TutORials in Operations Research: 39–63.

Garrido, A. (2010). Mathematics and AI, two branches of the same tree. *Procedia - Social and Behaviorial Sciences, 2*(2), 1133.

Lim, H. (2020). *7 Types of data bias in machine learning*. Retrieved from https://lionbridge.ai/articles/7-types-of-data-bias-in-machine-learning/

Linardatos, P., Papastefanopoulos, V., & Kotsiantis, S. (2021). Explainable AI: A review of machine learning interpretability methods. *Entropy, 23*(1), 18.

Liu, B. (2021). Weak AI is likely to never become strong AI, so what is its greatest value for us? *Computer Science*, arXiv:2103.15294.

Mehrabi, N., et al. (2019). A survey on bias and fairness in machine learning. *arXiv*.

Molnar, C., Casalicchio, G., & Bischl, B. (2020). Interpretable machine learning - A brief history, state-of-the-art and challenges. In *PKDD/ECML Workshops*.

Nikolic, D. (2017). Why deep neural nets cannot ever match biological intelligence and what to do about it? *International Journal of Automation and Computing, 14*, 532–541.

Ntoutsi, E., et al. (2020). *Bias in data-driven artificial intelligence systems - An introductory survey*. Wires.

O'neil, C. (2016). *Weapons of math destruction: How big data increases inequality and threaten democracy*. Crown Edition.

Radford, A., Metz, L., & Chintala, S. (2015). Unsupervised representation learning with deep convolutional generative adversarial networks. *arXiv*.

Rudin, C. (2019). Stop explaining black box machine learning models for high stakes decisions and use interpretable models instead. *Nature Machine Intelligence, 1*, 206–215.

Samek, W., et al. (2019). *Explainable AI - Interpreting, explaining and visualizing deep learning*. Springer.

Saxton, D., Grefenstette, E., Hill, F., & Kohli, P. (2019). Analysing mathematical reasoning abilities of neural models. In *ICLR Conference*.

Shaffi. (2020). AI and mathematics. Retrieved from https://medium.com/swlh/ai-mathematics-699a9ea2a0d6

Sun, Z., & Wang, P. P. (2017). A mathematical foundation of big data. *New Mathematics and Natural Computation, 13*(2), 83.

The pitfalls of intelligence: Artificial intelligence deems applications from women inferior - Amazon must react. *Focus* 12.10.2018.

Thesing, L., Autun, V., & Hansen, A. C. (2019) What do AI algorithms actually learn - On false structures in deep learning. *arXiv*.

Walch, K. (2019). Rethinking weak vs. strong AI. Retreived from https://www.forbes.com/sites/cognitiveworld/2019/10/04/rethinking-weak-vs-strong-ai/

Yapo, A., & Weiss, J. W. (2018). *Ethical implications of bias in machine learning*. HICSS.

Yosinki, J., Clune, J., Bengio, Y., & Lipson, H. (2014). How transferable are features in deep neural networks? *Advances in Neural Information Processing Systems*, arXiv:1411.1792.

Vincent Heuveline (born in Paris, 1968) has been Chief Information Officer of Heidelberg University since December 2018. He is also Director of the Computing Center of Heidelberg University. As a professor, he heads the "Engineering Mathematics and Computing Lab" (EMCL) at the Interdisciplinary Center for Scientific Computing (IWR) at Heidelberg University. In addition, he leads the research group "Data Mining and Uncertainty Quantification" at the Heidelberg Institute for Theoretical Studies (HITS gGmbH). His research interests include high-performance and data-intensive computing as well as software development with a special focus on application areas in medicine. In teaching, he deals intensively with the topic of IT security and AI—in addition to scientific computing—in the context of dedicated lectures and seminars. Prof. Heuveline is a member of the program committees of numerous international conferences on high-performance computing. As an expert and contact person, he advises representatives of industry on topics of digitization, the application-oriented use of numerical simulations, Big and Smart Data, AI, and IT security in the industrial environment.

Viola Stiefel studied Romance Studies (French and Italian) and History at Heidelberg University and received her PhD in French Literature in 2018. Since March 2021, she has been working as a consultant at the Heidelberg University Computing Center, where her work includes topics at the interface between the humanities, digitization, and AI.

Chapter 13
Statistics and Intelligence: A Chequered Relationship

Christel Weiss

Abstract This chapter examines the changing relationship between ‘statistics and intelligence’. It shows how statistics and intelligence influence each other. On the one hand, statistical methods are needed to measure the phenomenon of intelligence. On the other hand, the development of such methods on the part of mathematicians or stochastics requires cleverness, intellect and astuteness. This chapter also shows the power inherent in data, and the challenges faced by statisticians and subject representatives (who initiate and conduct studies) to uncover the information content hidden therein, to interpret the results of data analysis adequately, and to implement them consistently.

1 Introduction

Statistics and intelligence—how do they fit together? Whereas ‘intelligence’ is associated with universally recognized qualities such as a broad general education, sound specialist knowledge, practical talents or artistic talent, the term ‘statistics’ tends to arouse unpleasant feelings such as scepticism, mistrust or a lack of understanding.

The word intelligence is derived from the Latin verb ‘intellegere’. This is made up of the components ‘inter’ (between, in the middle) and ‘legere’ (to read, to select) and can therefore be freely translated as ‘to read between the lines’. In a very general sense, intelligence refers to the cognitive ability to meet new challenges with thinking skills and to develop solutions independently.

High intelligence has always been considered good. No one would be pleased, let alone proud, to be certified as having only a moderate intellect. On the other hand, in some circles it is not at all considered dishonourable to brag about one’s modest knowledge of mathematics or poor skills in statistics. In fact, it is considered an expression of critical thinking if a contemporary expresses doubts about the validity of a set of figures—be it poll results before a political election or risks

C. Weiss (✉)
Department of Medical Statistics and Biomathematics, Mannheim Medical Faculty of the University of Heidelberg, Mannheim, Germany
e-mail: christel.weiss@medma.uni-heidelberg.de

R. M. Holm-Hadulla et al. (eds.), *Intelligence - Theories and Applications*,
https://doi.org/10.1007/978-3-031-04198-3_13

determined in epidemiological studies—without any valid arguments. Often, the mention of a supposed counterexample or the reference to much quoted but little questioned sentences such as ‘You can prove anything with statistics’ is enough to meet with broad approval.

On the other hand, it is understandable: Those who know how to interpret the results of statistical analyses without bias are less likely to be manipulated. Progress in empirical sciences such as medicine, sociology or meteorology, for example, is based to a decisive degree on the diverse possibilities of complex analytical techniques. In order to recognize this, a certain degree of intelligence, in addition to openness and the ability to think critically, is not an obstacle.

In fact, there is enormous potential hidden in extensive data material: be it registers or characteristics collected in the context of empirical studies, or measured values routinely recorded during patient care in everyday clinical practice. These data collections contain valuable information, even if it is not necessarily obvious at first glance. A statistician is then faced with the challenging task of processing this data material, ideally together with a representative of the respective discipline, in such a way that new insights emerge from it. Therefore, researchers involved in planning and conducting empirical studies should have a certain intellect in order to plan the study adequately and to be able to draw meaningful conclusions from the results of the data analysis and implement them for the benefit of the general public.

Last but not least, the scientists who invented these statistical methods should also be mentioned. Most of them are mathematicians or natural scientists, who are generally considered to have at least an insular talent. Examples are *Carl Friedrich Gauss* (1777–1855), *Karl Pearson* (1857–1936) and *Sir Ronald Aylmer Fisher* (1890–1962), to whose genius we owe well-known statistical concepts that are still widely used even today.

After all, it is statistics itself that provides methods that make it possible to measure intelligence in the first place. In other words, without statistics, intelligence would be only a vague construct and it would be unattractive to fabulate about it. This article will take a closer look at these diverse and interwoven networks of relationships.

2 Statistical Methods for Measuring Intelligence

2.1 Historical Considerations

Intelligent people and elite classes enjoyed high esteem at all times. This explains why individuals have always sought to demonstrate their abilities and compare them with those of other contemporaries, for example, in the form of competitions. Olympic Games were already held in antiquity. There were also competitions in the Middle Ages, for example to evaluate the musical talent of minstrels.

A selection of the best—the elite—may also be socially relevant. An example can be read in the Old Testament: Thus, in the ‘Book of Judges’ of the Old Testament, chapter 7 reports how the judge Gideon selected an elite of the 300 best soldiers to fight against the nomadic tribe of the Midianites. The term ‘elite’ in the sense of an elite of achievement or intelligence appeared much later, when in the industrial era educated citizens sought to distinguish themselves from the broad mass of the uneducated in order to claim a socially privileged position or political power.

The term ‘intelligence’ was by no means precisely defined (which has not changed significantly to this day). The assessment of intelligence or the choice of an elite was usually made intuitively. The main aim was to identify highly gifted people; no attention was paid to moderately gifted or even less gifted individuals.

One of the first scientists to study the phenomenon of intelligence in depth was the British naturalist *Sir Francis Galton* (1822–1911), a cousin of *Charles Robert Darwin* (1809–1882). Inspired by Darwin’s theory of heredity, he founded the first chair of eugenics in London, the scientific discipline that aimed to promote the spread of favourable hereditary characteristics based on the findings of human genetics. Galton believed that intelligence was exclusively inherited; he paid no attention to environmental factors. Although personality traits such as intelligence were generally considered ‘incommensurable’ (not measurable), Galton firmly believed that this trait (like physiological parameters such as height) was quantifiable, even though no form of operationalization was known at that time. He also assumed that the measured values of a population are symmetrically arranged around a mean value and can be described by a Gaussian distribution. Galton’s successor, the statistician *Karl Pearson,* also held the view that intelligence, like numerous diseases, alcoholism or criminality, was solely hereditary. It was Pearson’s successor *Lionel Sharples Penrose* (1898–1972) (he made a name for himself as a psychiatrist, mathematician and geneticist), who suggested that intelligence was also influenced by numerous environmental parameters.

The researchers mentioned above dealt with the phenomenon of ‘intelligence’ mainly in the context of eugenic objectives. The recording of intelligence or the development of a suitable measuring technique were not the focus of their interest. Galton only devised a method for determining the intelligence of the masses: When visiting a folk festival in 1906, each visitor was allowed to estimate the weight of an ox. It turned out that the average value of the almost 800 individual estimates deviated only slightly from the actual weight of the animal—although many estimates were far above or below the true value. This result surprised Galton: He had actually intended to prove the ‘stupidity’ of the masses with this experiment. This phenomenon, according to which larger groups sometimes solve cognitive tasks more accurately than individual experts, has since then been confirmed several times (Hesse, 2013). However, this approach is not useful for measuring the intelligence of individuals.

2.2 Intelligence as a Complex Construct

The characteristic 'intelligence' is so complex that it eludes direct observation or precise measurement by means of a technical device. Subjective assessments on the part of the individual concerned or by another person, for example, on a visual analogue scale, are by their very nature very vague and not very objective.

How can such a characteristic be handled statistically? One possibility might be to use a surrogate characteristic that is easy to determine. The anatomist *Franz Joseph Gall* (1758–1828), for example, attempted to indirectly measure intelligence on the basis of the circumference of the skull, based on his theory, according to which the brain is the centre of all mental functions. In the early nineteenth century, many researchers held that intelligence was reflected in outward appearance and that parameters such as skull circumference, forehead width and height provided clues to special talents. Other scientists, such as the aforementioned Galton and the anatomist *Friedrich Tiedemann* (1781–1861), believed that a person's intellectual capacity could be inferred from the volume of their skull. Galton had correlated students' examination results with their estimated brain volume (in fact, Galton is considered one of the first scientists to use the correlation coefficient); Tiedemann had measured skulls for this purpose.

However, a suitable surrogate characteristic must ensure that it is closely related to the actual characteristic to be measured and that it provides reliable information. It soon became apparent that skull circumference did not meet these criteria. It is true that both Tiedemann and Galton believed they had identified an association between intellect and brain volume. In the meantime, however, it has been demonstrated that brain volume correlates at best very weakly with intelligence and is therefore unsuitable as a surrogate parameter (Wolf, 2021).A concrete reason for the development of a measurement method was given when compulsory education was introduced in France in the nineteenth century. This created the need for selection criteria in order to be able to promote pupils appropriately. In 1904, the psychologist *Alfred Binet* (1857–1911) was commissioned by the French government to develop a method for assessing the aptitude of pupils according to objective criteria. Together with his colleague *Théodore Simon* (1873–1961), he constructed the first intelligence test. This concept was based on the idea that the phenomenon of 'intelligence' should be regarded as a construct to be measured by several indicators (so-called items). To this end, Binet and Simon devised test items of varying difficulty to be solved by schoolchildren. Intelligence was determined on the basis of the number of correct solutions.

Subsequently, this test was modified and extended several times (which will be discussed in the next section). There were numerous supporters because this was the first quantitative method for identifying children with learning difficulties. Critics, on the other hand, argued that this test would only capture a partial aspect of intelligence. However, it is still undisputed that intelligence in general is to be regarded as a mental construct that can only be tapped indirectly via numerous indicators.

2.3 Intelligence Tests

Binet and Simon deserve credit for not only dealing theoretically with the phenomenon of ‘intelligence’ but also for devising a pragmatic method for operationalizing it. The challenge lay not so much in the practical implementation of the test, but rather in the choice of suitable test items, which in their diversity should divide the students into different performance groups as sharply as possible.

The range extends from very simple tasks that a toddler should be able to do (such as tracking a lit match with the eyes) to more difficult ones (for example, counting backwards) to very challenging tasks that generally only older children can do (for example, finding rhyming words). There are usually six tasks for each age level. The highest age level whose tasks a child can completely master is the so-called basic age. To determine the intelligence age, 2 months are added to the basic age for each additional solution of a higher age group. On average (in relation to the children of a certain age group), the age of intelligence corresponds to the age of life. An intelligence age that is significantly lower than the life age indicates that targeted support measures are useful for the child in question.

This test made it possible for the first time to quantify intelligence and compare it between individuals of the same age group. Subjective teacher ratings regarding the performance of schoolchildren were replaced by an objective and comprehensible method of measurement. The test score is a numerical value that is easy to determine and simple to interpret. However, the Binet–Simon test is not without limitations: Comparisons between different age groups prove problematic because the difference between intelligence and age is more severe in younger children than in older ones.The psychologist *William Louis Stern* (1871–1938) solved this problem by putting intelligence and age into a ratio and multiplying it by 100. This is how the intelligence quotient *IQ was* created:

$$\text{IQ} = \frac{\text{intelligence age}}{\text{age of life}} \cdot 100$$

Based on this definition, it is guaranteed that the *IQ of* an average intelligent child of any age group is 100 (Stern, 1912). Thus, a 10-year-old child with an intelligence age of 11 years has an *IQ of* 110, while for a 5-year-old child with an intelligence age of 6 years an *IQ of* 120 results.

But even this intelligence quotient has limitations with regard to its application: Since intelligence increases more slowly with higher age than it does in childhood, according to Stern’s formula an individual’s *IQ* would steadily decline over the course of their lifetime. Therefore, this method is not useful for adults.

To address this problem, the psychologist *Lewis Madison Terman* (1877–1956) of Stanford University developed several age-specific test variants for children and adolescents as well as for normally and above-averagely gifted adults. He standardized the results within each variant—in such a way that the *IQ* of the respective population is subject to a Gaussian distribution with a mean value of 100 and a standard deviation of 15 (cf. Fig. 13.1). The so-called Stanford–Binet test soon became a standard instrument in psychology and in school counselling. From the properties of the Gaussian distribution it follows that in each case values above or below 100 are measured for half of those tested; approximately two-thirds achieve *IQ values* between 85 and 115 points (this is the interval 'mean ± one standard deviation'). Only about 5% of all *IQ scores* are further than two standard deviations from the mean. Accordingly, approximately 2.5% of population members are found to have *IQ scores* below 70, which is associated with a decrease in cognitive ability. The other extreme—an *IQ* of 130 and above—is also achieved by only 2.5%. These people are considered highly gifted.

Ultimately, Galton's ideas had become reality: Intelligence could be regarded as a quantitative, measurable characteristic whose variability within a population was described by the ideal-typical model of a normal distribution. This made it possible to classify people into average, below-average and above-average subgroups according to objective criteria.

Another important contribution to intelligence research was made by the British psychologist *Charles Edward Spearman* (1863–1945). While observing schoolchildren, he noticed that the results of various achievement tests correlated positively. He therefore assumed that all intellectual performance is based on a uniform form of intelligence. This is captured in a general factor, the so-called *g-factor* ('general intelligence') (Spearman, 1904). In addition, he postulated, there are group factors (the so-called *s-factors,* such as verbal abilities or spatial reasoning), one of which is required to solve a specific problem.

David Wechsler (1896–1981), a student of Spearman, was not convinced of the meaningfulness of the academic definition of intelligence and the significance of the *IQ tests* used at that time. He understood intelligence in a broader sense that included non-intellectual aspects. In 1939 he presented a series of several individual tests (scales). The tests include the ability to think logically, working memory, language

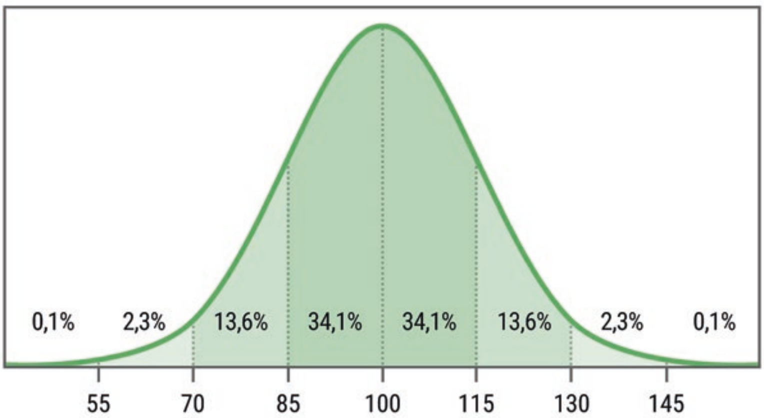

Fig. 13.1 Gaussian bell curve describing intelligence quotient with expected value 100 and standard deviation 15. (From Wolf (2021))

comprehension, processing speed and the ability to concentrate. As with the Stanford–Binet test, the values within an age group are normally distributed with an expected value of 100 and a standard deviation of 15.

Originally, the Wechsler test was designed for adults and was mainly used in the USA. German test versions have been available since 1956 and are known as the 'Hamburg–Wechsler Intelligence Test'. Since then, these versions have been revised several times and adapted to new findings of current research (Boake, 2002).

Wechsler adhered to Spearman's two-factor theory of a general and a specific intelligence factor. In each Wechsler intelligence test, the 'General Ability Index' is determined, comparable to Spearman's *g-factor*. *IQ tests* according to Wechsler are now among the most widely used instruments in the world for discovering talent, assessing candidates for job applications, identifying suitable applicants for university, and identifying students with learning difficulties or gifted students.

3 The Influence of Intelligence in Data Analysis

3.1 Intelligence of the Data

Man is curious by nature. That is why data—in its very general sense—has been collected since the beginning of mankind: Humans use their sense organs to record their environment, they use language to communicate, and they use their fingers to count. It is therefore not surprising that the determination of frequencies has established itself as the oldest form of statistical data collection.A first form of systematic data collection emerged from the sixteenth century onwards, when the first nation states flourished. The data collected served primarily the purpose of describing essential characteristics of a population and enabling administrative planning. From the Renaissance onwards, astronomers and natural scientists such as *Johannes Kepler* (1571–1630) and *Galileo Galilei* (1564–1641) collected data to derive scientific laws. A few years later, the merchant *John Graunt* (1620–1674) in London and the Prussian field preacher *Johann Peter Süßmilch* (1707–1767) in Berlin drew up mortality tables based on entries in church records and estimated life expectancies from the data thus obtained. Since the beginning of the industrial age in the eighteenth century, technical devices have been available with which physical quantities can be measured. The first empirical studies in the field of epidemiological and clinical research were carried out in the nineteenth century: The English physician *John Snow* (1813–1858) succeeded in containing a cholera epidemic in London in 1849 after collecting and analysing data from affected patients and controls who were not ill. The French physician *Pierre Charles Alexandre Louis* (1787–1872) used suitable data to prove that the method of bloodletting, which had been frequently used until then, was useless or even harmful in most patients. The Hungarian gynaecologist *Philipp Ignaz Semmelweis* (1818–1865) was able to prove, on the basis of systematic investigations combined with meticulous data documentation, that the then feared puerperal fever was caused by a lack of hygiene.

These examples show that there is enormous potential in data: Both scientific laws and empirical findings in medicine or the social sciences were and are verified based on an adequate amount of data. Data are the foundation of any statistical analysis. With their help, events can be explained and correlations illuminated.

But is data intelligent? Certainly not in the sense of a cognitive ability. Data per se cannot develop independent solutions. They do not speak for themselves; they do not reveal anything on their own. Information can emerge from data—but only for someone who is able to extract this information. For example, a *Body Mass Index* (BMI) of 40 kg/m^2 says that the person in question suffers from obesity. However, this is only apparent to someone who knows the definition of BMI and how this characteristic is distributed. A conglomerate of data is capable of telling an anecdote—but only to someone who knows how the data came about and in what context it stands. Only with this background knowledge is one able to combine individual data into a meaningful whole.

Any extensive data material is worthless if it is not adequately processed. This is illustrated by the example of weather forecasting: Thousands of measuring stations and satellites in all parts of the world permanently supply data in an almost unmanageable mass. This has the potential to accurately forecast the weather for the next day in virtually all regions worldwide. However, this requires powerful computers, sophisticated technology, professional data management, complex mathematical algorithms and, last but not least, technically skilled meteorologists who master and process the flood of data and know how to interpret the results.

Data can be of high or low quality. This concerns the way they are collected, their precision, their reliability and their completeness. Data do not fall from the sky. Therefore, in the planning phase of a study, care should be taken to select variables that are meaningful and relevant to the research question and that represent reality validly, and that the data are collected completely and correctly and documented carefully. Even if the collection of large amounts of data does not pose a significant problem from a technical point of view, they still require competent handling in order to exploit the potential they contain.

3.2 Intelligence of the Methods

Are statistical methods intelligent? This question must also be answered in the negative. Methods are used to process data efficiently. The intelligence hidden in them should be attested to their developers.

As a simple example, consider the arithmetic mean. One of the first known applications was devised by the astronomer *Tycho Brahe* (1546–1601), an associate of Johannes Kepler. In order to counter the inaccuracies of the clock movements available at the time, Brahe used several clocks simultaneously and calculated the mean value from the time durations determined. An ingenious idea in the late sixteenth century!

At the beginning of the twentieth century, inductive statistics made rapid progress. The chemist *Sealy Gosset* (1876–1937), starting from a practical problem (as an employee of the *Guinness* brewery, he wanted to estimate the mean values of beer ingredients), devised the *t-distribution,* which is used for the famous *t-location tests* and the construction of confidence intervals. During the same period, the aforementioned scientists Pearson and Spearman published the correlation coefficients named after them for quantifying the strength of a relationship between two variables. The determination of the parameters of a regression line had already been derived about a 100 years earlier by the well-known mathematician Gauss based on the method of least squares. In the 1950s, the British statistician and geneticist *Sir Ronald Aylmer Fisher* laid the foundation for variance analyses. His motivation: He wanted to evaluate the influence of different soil qualities on plant growth.These are just a few examples from the list of outstanding scientists who have significantly enriched statistics. They pondered their methods long before computers were available to perform the sometimes very complex calculations. They probably never dreamed that the techniques they devised would still enjoy great popularity decades or even centuries later.

Since the 1970s, powerful computers and user-friendly software have stimulated the further development of statistics. This mainly concerns multivariate methods, exploratory data analysis, Monte Carlo methods or meta-analyses (to name just a few examples). With the accelerated technological progress, the need for special statistical methods arose. Mathematicians were faced with the challenge of devising methods to test the reliability and validity of a measurement method (e.g. for measuring instruments used in diagnostics and therapy or for psychometric measurement procedures). In this way, Cohen's kappa index (Cohen, 1960) and the intraclass correlation coefficient were developed as measures of agreement (Shrout & Fleiss, 1973), Cronbach's alpha for quantifying the internal consistency of a questionnaire (Cronbach, 1951) or the Bland–Altman analysis (Bland & Altman, 1986), which can be used to assess the level of agreement between two quantitative measurement methods.

All the scientists mentioned in this section proved to be impressively intelligent, meeting new challenges with ingenious thinking and developing solutions on their own.

3.3 Intelligence of the Users

Statistical measures and methods of analysis can get to the heart of things. The most important properties of a data series or the strength of a correlation can be quantified by means of suitable measures of location, dispersion or association; the difference between two groups can be demonstrated by a statistical test and the dependence of a target variable on several influencing variables can be explained by a multiple model. This requires competent statisticians to select these procedures.

Are the users of statistics intelligent? That would be desirable in any case! Statisticians generally have a dubious reputation; statistics as a science is considered mysterious and unattractive. Statistics is indeed a branch of mathematics, i.e. an exact science. It is oriented towards data, i.e. hard facts. Nevertheless, the results of its methods are influenced by chance. On the one hand, the *p-value* (the probability of error) may be regarded as an exact measure of evidence for the plausibility of the null hypothesis. On the other hand, this value reflects the uncertainty with which the result of a statistical test is afflicted.How can data be analysed efficiently under this premise? In order to generate meaningful data, select adequate statistical methods and create a statistical model that best describes reality based on the collected data, you need not only methodological knowledge and empirical experience, but also a keen sense of observation and a deeper scientific understanding of the underlying issue, open-mindedness and curiosity—because the results of the analysis are usually compiled for another research field.

The optimal data analysis is by no means predetermined. It is not enough, and it does not always make sense, to adhere strictly to guidelines; rather, independent and critical thinking is required at every stage of the study. For each question, several approaches seem conceivable (although each statistical method is linked to certain preconditions that must be checked in advance). Therefore, before preparing the data, it is important to consider: What is the study design? Are the data correct? How can this be checked? How do you deal with missing values? How do you deal with outliers? Which analysis methods are suitable? What should be considered when generating a multiple model?

Although there is general consensus that the result of a statistical analysis is considered significant if the *p-value* is below 0.05, seemingly exact numerical results are open to various interpretations. Therefore, one should question: How did a result come about? How strong is the proven relationship? Is it causal? Are the results possibly subject to bias? How precise is the estimate? And finally: Is the result relevant from a technical point of view? What consequences should be drawn from it in terms of content?

In order to clarify these issues, both statisticians and subject representatives who initiated the study in question should be prepared to acquire basic knowledge of the other subject area. It proves productive when colleagues from several disciplines, in an interdisciplinary exchange, examine the result of the data analysis from different perspectives, in a combination of methodological–statistical and empirical–scientific viewpoints, critically question it, discuss possible applications and limitations. In addition to tolerance and thoughtfulness, a certain amount of common sense is also an advantage.

These skills reveal the intelligence of all scientists involved in a study, especially statisticians. Their professional activity is characterized by the fact that they are involved in the planning and implementation of studies from various disciplines. To do this, they must be prepared to face intellectual challenges, to familiarize themselves with areas outside their field, to develop solutions independently and to look beyond their own horizons.

3.4 Consumer Intelligence

Data analyses serve not only scientific progress but also societal benefit. For example, if a risk study shows the association between an etiological factor and a disease, or if a therapy study demonstrates the efficacy of a new drug, these findings are only useful if as many people as possible benefit from them. If a representative survey is conducted before a political election, the values obtained are of general interest. Therefore, the results from a data analysis must be made available to the public.In fact, hardly anyone can escape statistics—neither in everyday life nor in scientific discourse. Various media ensure that we are kept up to date on current events virtually around the clock with percentages, tables, diagrams and averages.

Every doctor has the possibility of permanently accessing knowledge available worldwide via databases. This ensures (at least in theory) that every decision they make, for example, regarding the diagnosis or therapy of a patient, is based on the latest research.

Some contemporaries, however, feel uncomfortable in the face of the wealth of information that is pouring in. They fear being manipulated because they are told that they can hardly trust their own minds and their individual experiences. Others are sceptical because they believe that progress (in medicine, for example) is nowhere near as rapid as the numerous publications in international journals suggest. ‘Statistical reasoning will one day be as important to responsible citizens as the ability to read and write.’ This statement, attributed to the English writer *Herbert George Wells* (1866–1946), shows very clearly that statistical thinking already encountered difficulties in his time. Unfortunately, little has changed in this regard to date.

Graphical representations are excellent for dramatizing trivial effects or for concealing undesirable effects. Figures are also sometimes less objective than they seem. Relative risks in particular can easily cause confusion. For example: In the 1990s, alarming information regarding the contraceptive pill was disseminated in the British media. The use of a certain preparation allegedly increased the risk of thromboembolism by a whopping 100%! Faced with this figure, many women immediately stopped taking the pill in a panic, assuming that this life-threatening side effect was certain to happen to them one day. Thousands of unwanted pregnancies and abortions were the result of this misunderstanding. The 100% quantified only a relative increase in risk; the actual risks were only 1/7000 and 2/7000, respectively.—A critical approach to probabilities is also needed in the use of diagnostic tests and screenings (by both physicians and patients) so that the test result is interpreted appropriately depending on the prevalence (Weiß, 2021).

Another bad habit in dealing with probabilities consists in pointless comparisons. Here is an anecdote: Rudy Giuliani, former mayor of New York, who had prostate cancer, once announced that he considered himself lucky to be treated in the USA. There, he said, the survival rate for this condition was almost twice as high as in England (82% versus 44%). This difference is undoubtedly considerable; nevertheless, the comparison is misleading. In the USA—unlike in England—screening is offered nationwide. Therefore, significantly more prostate carcinomas are diagnosed in US men than in British men. Carcinomas in the US are usually detected at an earlier stage and are less aggressive than carcinomas that show up later with clinical symptoms. In contrast, it would be fair to compare disease-specific mortality rates in relation to all adult males in each country: These are 26 and 27 per 100,000 men per year, respectively. Further examples of improper interpretation of probabilities can be found in Gigerenzer et al. (2007).

Data has the power to explain developments and forecast events. However, they can also, if improperly analysed, distort results and mislead. Data do not lie, but those who manipulate data, show only certain findings or conceal undesirable results do. Communicating probabilities and uncertainties in an understandable way is a challenge. Therefore, researchers or journalists who prepare and disseminate the results of statistical analyses should strive for objectivity in their presentation, present results that are as meaningful as possible, and openly discuss the limitations of their investigations. Readers of a publication should not be blinded by small *p-values,* but should critically assess the study design and finally try to find an answer to the question: For which group of people or for which object of research are the described results useful?

These remarks make it clear: Consumers of statistics also need intellectual abilities to extract relevant information from numbers and diagrams—both in the high spheres of science and in the low spheres of everyday life.

4 Conclusions

4.1 The Influence of Intelligence Research on Statistics

Statistics made intelligence research possible, because with its help more meaningful measuring instruments were developed. On the other hand, intelligence research had a massive and lasting influence on statistics. Its pioneers—Francis Galton and Karl Pearson—are considered the inventors of correlation and regression. These techniques were taken up in subsequent years for innumerable applications, especially in the life sciences, but also in psychology and economics. Galton was obsessed with measurement and fascinated by the Gaussian distribution. He adopted this concept from his colleague, the statistician *Adolphe Quetelet* (1796–1874), who had recognized the importance of this distribution for describing human characteristics several years earlier. Unlike Quetelet, however, Galton did not orient himself to an average person, but focused his attention on the variability of individuals. Whereas Quetelet considered major deviations of a measured value from the mean to be erroneous or abnormal (indeed, in Quetelet's day, the Gaussian distribution was called 'la loi des erreurs'), Galton used this concept to enable classification. To this end, he introduced new measures of location, namely the median and the quartiles, which decompose a population into two and four equally weighted subgroups, respectively. As a measure of dispersion, he preferred the quartile distance as the width of the interval in which the middle 50% of the measured values lie.

The methods devised by Galton and Pearson have become established as standard tools in statistics. Pearson is considered a pioneer of biometrics, the scientific discipline that deals with the measurement of physiological characteristics in living beings and the associated methods of analysis. Galton is credited with having addressed questions of intelligence research for the first time and with having recognized the importance of the normal distribution for describing a population.

Spearman also significantly influenced statistical science. His contributions to intelligence research not only provided the rank correlation coefficient named after him but also led to the development of factor analysis (Spearman, 1914). With this, he founded psychometrics—a discipline dedicated to the development of measurement instruments to capture personality traits. He succeeded in extracting the general group factor *g* and reducing the results of intelligence tests to a few variables (Fig. 13.2).

While Spearman's model is based on the idea that every cognitive performance is composed of a general factor and a specific factor independent of it, and that all these factors are independent of each other, Spearman's colleague *Louis Leon Thurstone* (1887–1955) took a somewhat more complex approach. He identified seven primary factors that should be the basis of human intelligence and should not necessarily be considered independent: Numeracy, Language Comprehension, Spatial Imagination, Memory, Reasoning, Verbal Fluency and Perceptual Speed. He

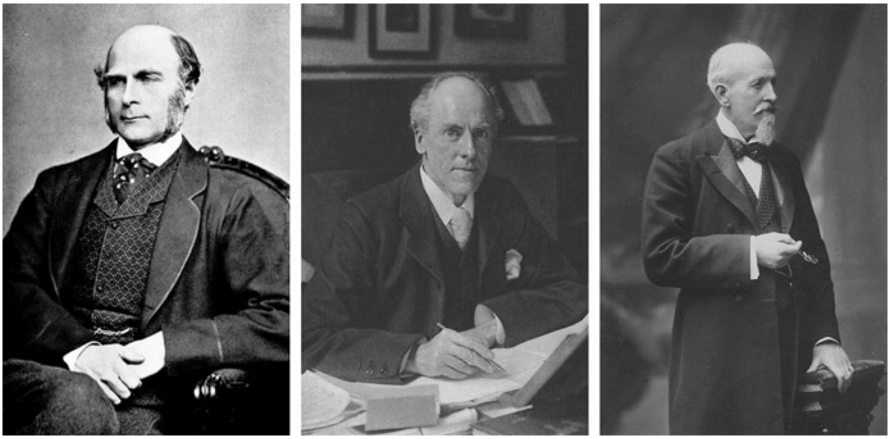

Fig. 13.2 Pioneers of intelligence research: Francis Galton (naturalist), Karl Pearson (mathematician) and Charles Spearman (psychologist). (Image source Galton: https://de.wikipedia.or g/wiki/Francis_Galton, Image source Pearson: https://de.wikipedia.org/wiki/Karl_Pearson; Image source Spearman: https://de.wikipedia.org/wiki/Charles_Spearman)

thus generalized Spearman's method to a multivariate factor analysis. Today, this technique is considered a universally applicable tool with the help of which it is possible to conclude from measurable phenomena to their not directly visible causes.

4.2 Applications and Limitations of Intelligence Tests

Binet and Simon's test was the first measurement instrument for intelligence. This concept was a major achievement at the beginning of the twentieth century and was subsequently revised several times and adapted to new findings. It is still widely used—despite the fact that scientists have not yet been able to agree on a uniform, comprehensive definition of intelligence. Its quantification by means of a normally distributed variable has made a major contribution to establishing intelligence research as a branch of psychology that investigates the causes and effects of the various forms of intelligence. An important representative is the already mentioned Penrose, who systematically investigated the causes of learning disabilities for the first time in his 'Colchester Study'.Nevertheless, these tests are not without controversy. One frequent criticism is that a test cannot fully capture intelligence in all its complexity. Sometimes it is even questioned whether such a test measures what it claims to measure and whether one can rely on the result. The slightly modified quotation from the American psychologist *Edwin Boring* (1886–1968), 'Intelligence is what an intelligence test measures', cannot provide a satisfactory answer to these questions.

On the other hand, it is a fact that none of these tests claims to capture all facets of a person's intelligence. *IQ*—like any statistical model—is a simplified and thus imperfect representation of reality. The test result provides information about the extent to which the person tested is capable of solving certain tasks, and is in this respect quite meaningful. In addition, very pragmatic reasons can be given for the popularity of these tests. How could individual performance assessments or intelligence research be possible if there were no instrument that provided objective and comparable results?

In order to assess the suitability of an intelligence test, two quality criteria are usually used: reliability and validity. *Reliability* indicates the extent to which the test results are reproducible when the test is repeated under similar conditions. Several studies have shown that test scores correlate strongly when a group of individuals take two tests with a certain time interval (with correlation coefficients ranging from 0.7 to 0.9 (Schuerger & Witt, 1989)). *Validity*, on the other hand, is more difficult to assess: this criterion indicates whether the test really measures what it claims to measure. Nevertheless, it has been shown that Spearman's *g-factor* correlates positively with a number of personality traits: the level of school completion, the final grade of studies, professional success, income, life expectancy and general well-being. This speaks for the validity of the intelligence tests, since these characteristics are commonly associated with intelligence.

However, it should be added that the degree of these correlations is low to moderate. *IQ* is a theoretical construct that says nothing about how a person uses their abilities. Therefore, in individual cases, the result of an *IQ test in* a school child has only a low prognostic relevance for later happiness in life. Life experience teaches us that intelligence and a good education are only part of what determines professional success and social recognition. Important components are also other cognitive abilities that are ignored in the usual intelligence tests: Creativity, imagination, curiosity, discipline, perseverance, and emotional and practical intelligence. Emotional intelligence refers to the ability to perceive and respond appropriately to one's own emotions and the emotions of one's peers. Practical intelligence is about being able to put theoretical knowledge into practice. These qualities are just as important for a successful life as academic intelligence. However, to date there are hardly any tests that could validly test this. This may be one reason why the relevance of intelligence tests is sometimes overrated.

4.3 Intelligence and Environment

It should not go unmentioned that the theories of Galton and Pearson also had extremely negative effects. Under the erroneous assumption that environmental factors have at best only a very slight effect on personality, the two scientists envisioned optimizing the innate characteristics of the 'human race' by eradicating undesirable genetic material. This idea spread rapidly and found supporters worldwide. Under the National Socialists, this 'scientifically based' eugenics finally reached its perfidious perfection. In the meantime, Galton's and Pearson's theories have long since been disproved.

In the context of twin research, it has been shown that the *IQ scores of* identical twins (who are known to share the same DNA) are closer together than those of fraternal twins, and that these in turn are more similar than the *IQ scores of* normal siblings. These results reveal that intelligence is both hereditary and determined by environmental influences. Thus, Galton's theory, which conjectured that intelligence was solely hereditary, was refuted by his own methods (namely, the use of correlation coefficients). Today, there is general consensus that intelligence and other complex personality traits are influenced by a multitude of genes and diverse environmental factors, and that it is precisely this diversity that is the basic prerequisite for the survival of a population.

Statistically, this interaction can be described as follows: The variance of intelligence (the square of the standard deviation) is composed additively of the genetically determined variance and the environmentally determined variance. Heritability is defined as the proportion of genetically determined variance in the total variance. It thus refers to the variability *within* a population, but not to intelligence differences *between* several subgroups. Thus, a heritability of 50% (as has been demonstrated for Central Europe) means that half of the differences in intelligence within a population are genetically determined. However, this value in no way implies that an individual owes half of its intelligence to its genes or to the environment.

This finding has far-reaching consequences. Differences between social classes in terms of average *IQ* cannot be explained by genetic influences alone (as Galton assumed). Rather, it can be assumed that different living conditions, which become apparent in education, health or wealth, are decisive for this.

That environmental factors are of great importance is impressively confirmed by the so-called Flynn effect (named after its discoverer, the political scientist James Robert Flynn, 1934–2020). This effect describes that in industrial nations the average *IQ* has increased by 5–25 points within one generation since measurements began (Flynn, 1987). Now, it can hardly be assumed that people living today are vastly superior to their ancestors in terms of intellectual ability. A more plausible explanation would be that—in addition to longer schooling, better nutrition and medical care—the specific skills required in *IQ tests* (such as language comprehension, logical–analytical thinking or working under time pressure) are better trained nowadays than in earlier times. However, this effect seems to have stagnated in recent years (Schaarschmidt, 2019). The reasons for this phenomenon are not conclusively understood. It is conceivable that this does not affect all cognitive abilities. Perhaps the stagnation is also due to the fact that an optimum has now been reached with regard to environmental factors in large parts of the population.

Furthermore, it has been shown that *IQ* remains fairly stable over the course of a person's life. When comparing test results obtained from the same persons as schoolchildren and as adults, correlation coefficients of up to 0.7 were found (Deary, 2014). On the other hand, it is clear that *IQ* is not an absolute personality trait. In fact, it has been shown in numerous studies that environmental factors such as upbringing, education, social environment, cultural influences or targeted encouragement can passively influence *IQ*—in both negative and positive directions. Furthermore, every individual can actively counteract the reduction of their *IQ* by exercising, eating a healthy diet or acquiring a new skill (e.g. learning a foreign language).

4.4 Concluding Remarks

It is certainly no coincidence that many statisticians were concerned with the measurement of intelligence. On the one hand, they were inspired by statistics; on the other hand, they gave statistics enormous impetus.

Recently, buzzwords such as *Big Data*, *Data Science*, *Artificial Intelligence* (AI) or *Machine Learning,* which are often used synonymously, have been increasingly discussed. As the name suggests, Big Data refers to an immensely large amount of data, often compiled from multiple data sources, that needs to be analysed in a short period of time. Artificial intelligence is powerful software whose goal is to identify patterns in the plethora of data. 'Machine learning' is a subfield of AI that aims to develop solutions and make decisions on its own. Nevertheless, all these techniques are based on algorithms designed by humans, and humans alone are responsible for interpreting the results that emerge from statistical analyses.

It remains to be said: An immense amount of data, extremely fast high-performance computers, optimal data management, precise pattern recognition and highly efficient statistical analysis methods are no substitute for human intelligence. In order to arrive at new insights, not only intelligence is required but also a host of additional skills: a solid education, sufficient experience, the willingness to constantly educate oneself, intuition, acumen, enthusiasm, the ability to work in a team and the unconditional will to get to the bottom of things. This applies to all researchers who plan or conduct empirical studies, analyse data and interpret their results. This applies equally to journalists and authors of scientific papers who publish the resulting findings, as well as to those who put these findings into practice. Last but not least, consumers of statistics need to have a clear mind and a healthy scepticism so that they are not blinded by figures or diagrams but are instead informed in an unbiased way.

References

Bland, J. M., & Altman, D. F. (1986). Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet, 1*(8), 307–310.

Boake, C. (2002). From the Binet-Simon to the Wechsler-Bellevue: Tracing the history of intelligence testing. *Journal of Clinical and Experimental Neuropsychology, 24*(3), 383–405.

Cohen, J. (1960). A coefficient of agreement for nominal scales. *Educational and Physiological Measurement, 20*, 37–46.

Cronbach, L. J. (1951). Coefficient alpha and the internal structure of tests. *Psychometrika, 16*, 297–332.

Deary, I. J. (2014). The stability of intelligence from childhood to old age. *Current Directions in Psychological Science, 23*(4), 239–245.

Flynn, J. R. (1987). Massive IQ gains in 14 nations: What IQ tests really measure. *Psychological Bulletin, 101*(2), 171–191.

Gigerenzer, G., Gaissmaier, W., Kurz-Milcke, E., Schwartz, L. M., & Woloshin, S. (2007). Helping doctors and patients make sense of health statistics. *Psychocological Science in the Public Interest, 8*(2), 53–96.

Hesse, C. (2013). Schwarmintelligenz. In *Why mathematics makes you happy* (Chap. 122, 4the edn). Verlag C.H. Beck.

Schaarschmidt, T. (2019). Flynn effect. Why intelligence does not continue to rise. In: *Spectrum psychology* 2. https://www.spektrum.de/news/warum-die-intelligenz-nicht-weiter-steigt/1612044

Schuerger, J. M., & Witt, A. C. (1989). The temporal stability of individually tested intelligence. *Journal of Clinical Psychology, 45*(2), 294–302.

Shrout, P. E., & Fleiss, J. L. (1973). Intraclass correlation: Uses in assessing rater reliability. *Psychological Bulletin, 1*, 30–46.

Spearman, C. (1904). "General Intelligence", objectively determined and measured. *The American Journal of Physiology, 15*, 201–293.

Spearman, C. (1914). The theory of two factors. *Psychological Review, 21*, 101–115.

Stern, W. (1912). *Die psychologischen Methoden der Intelligenzprüfung und deren Anwendung an Schulkindern*. Published by Johann Ambrosius Barth.

Weiß, C. (2021). Statistik kritisch beleuchet. In: M. S. Kupka (Ed.), *Reproductive medicine. Facts and figures for counselling* (Chap. 14). Urban & Fischer Verlag.

Wolf, C.. *More brains, more brains*. Retrieved April 10, 2021, from Spektrum.de https://www.spektrum.de/news/mehr-hirn-mehr-koepfchen/1618626

Christel Weiss is Professor of Biomathematics and Epidemiology at the Mannheim Medical Faculty of Heidelberg University. Her responsibilities include teaching courses for medical students and master's course graduates, seminars, and advising physicians, research assistants, and doctoral students on planning and conducting clinical and epidemiological studies. Ms. Weiß is the author of the textbook "Basiswissen Medizinische Statistik" (published by Springer-Verlag, seventh edition), the guidebook "Promotion. Die medizinische Doktorarbeit – von der Themensuche bis zur Dissertation" (together with Prof. Dr. Axel Bauer, published by Thieme-Verlag, fourth edition) as well as co-author of numerous papers and book contributions.

Part IV
Artificial and Human Intelligence

Chapter 14
Human and Artificial Intelligence: A Critical Comparison

Thomas Fuchs

Abstract Advances in *artificial intelligence and robotics* increasingly call into question the distinction between simulation and reality of the human person. On the one hand, they suggest a computeromorphic understanding of human intelligence, and on the other, an anthropomorphization of AI systems. In other words: We increasingly conceive of ourselves in the image of our machines, while conversely we elevate our machines to new subjects. So what distinguishes human intelligence from artificial intelligence? The essay sets out a number of criteria for this.

1 Introduction

With the advances in artificial intelligence, we mortal humans seem to be getting increasingly caught up in a rearguard action: Intelligent systems are beginning to adapt themselves, to "learn" as they say, and in many cases are outperforming human intelligence. In chess, Go, or poker, humans no longer stand a chance against them. Planning, voting, decision-making, even driving seem to be increasingly taken away from us. The corresponding announcements by AI engineers, futurologists, and transhumanists virtually outdo each other:

> The fact is that AI can go further than humans, it could be billions of times smarter than humans at this point.[1]

[1] I. Pearson (2008). "The Future of Life. Creating Natural, Artificial, Synthetic and Virtual Organisms." *European Molecular Biology Organization (EMBO) Reports 9* (Supplement 1): 75–77. [3] Ray Kurzweil, as cited in L. Greenemeier (2010). "Machine Self-awareness." *Scientific American* 302: 44–45.

Abridged version of an essay in the volume: T. Fuchs (2020). *Verteidigung des Menschen. Grundfragen einer verkörperten Anthropologie*. Frankfurt/M.: Suhrkamp, pp. 21–70.

T. Fuchs (✉)
Department of General Psychiatry, Center for Psychosocial Medicine, Heidelberg University Hospital, Heidelberg, Germany
e-mail: thomas.fuchs@med.uni-heidelberg.de

R. M. Holm-Hadulla et al. (eds.), *Intelligence - Theories and Applications*,
https://doi.org/10.1007/978-3-031-04198-3_14

> Machines will follow a path that mirrors the evolution of humans. Ultimately, however, self-aware, self-improving machines will evolve beyond humans' ability to control or even understand them.[2]

Ray Kurzweil, AI researcher and head of development at Google, has announced the "Singularity" in 2045, the point in time when artificial intelligence will gain consciousness, an exponential progress toward a "superintelligence" sets in, and thus a new age will begin.

Even if such full-bodied forecasts are regularly corrected—at least the language of AI research already anticipates this development. There are almost no human abilities that are not already attributed to artificial systems: perceiving, recognizing, thinking, reasoning, evaluating or deciding. Conversely, human consciousness appears to many today to be nothing more than a sum of algorithms, a complex data structure in the brain that could in principle also be realized by electronic systems and is no longer bound to the living body.

The computer paradigm of the human mind has a long history. As early as 1936, mathematician Alan Turing developed the idea of a digital computer and later proposed his famous Turing Test: A group of reviewers communicates for a long time in writing with a human and with a computer, without having any other contact with them. If the evaluators cannot distinguish between a human and a machine, then, according to Turing, there is nothing to prevent us from recognizing the computer as a "thinking machine." Thinking is thus defined in purely behaviorist terms, namely as the output of a computational system, be it the brain or the computer. The Turing test is based on the indistinguishability of simulation and original: What acts as intelligently as we do *is intelligent,* full stop.[3]

At least the simulation is now currently making tremendous progress—to the point where the question of how it differs from the original begins to arise. What distinguishes consciousness from its simulation? Does the old principle really apply here? "If something looks like a duck, swims like a duck, and quacks like a duck, then it is a duck."An idea of the future problems that this question could pose is given by "Sophia," a humanoid robot from the company *HansonRobotics, which is* currently in the media worldwide.[4] Sophia has human-like facial expressions (modeled after Audrey Hepburn), displays various emotional expressions, a modulated tone of voice, and makes eye contact with the other person. She answers relatively complex questions, including about herself, can recognize people, and jokes about the English weather at an appropriate point in a London talk show.

Of course, all this is just a bluff. This became obvious when Sophia was confronted with a question apparently unknown to her, namely "Do you want to kill people?" and gave as an answer, "Okay. I want to kill people." The answer was

---

[2] R. Kurzweil (2005). *The Singularity Is Near. When Humans Transcend Biology*. New York: Penguin.

[3] Cf. A. M. Turing (1950). "Computing Machinery and Intelligence." *Mind* 59: 433–460.

[4] C. Weller (2017). "Meet the first-ever robot citizen, a humanoid named Sophia that once said it would destroy humans." *Business Insider Nordic. Haettu*, 30 Jg.

merely parroted; Sophia, of course, did not understand a word of what she was asked. Still, the effect of this robot is startling. Sophia is already approaching the *uncanny valley*, as robotics calls the threshold beyond which an android's human-likeness creates in us a sense of eeriness, but at the same time fascination. It is the feeling that arises when the realms of the dead and the living can no longer be clearly distinguished from one another. When will the *uncanny valley* be crossed and a future Sophia become indistinguishable from a charming, intelligent woman?

This threshold is crossed in *Her*, a science fiction film by Spike Jonze from 2013: Theodore, a shy but sensitive man, falls in love with a software program called Samantha with an erotic voice that, as a "learning program," apparently develops human sensations. The more Theodore falls for her, the more indifferent he becomes to whether she is a real counterpart or just a simulation—the gratifying fit is enough. However, the love between human and program fails in the end due to Samantha's further development—she makes virtual contact with thousands of other humans and operating systems and "falls in love" with them, so that she finally "leaves" Theodore.

The projective empathy of man with his own artificial creatures is, of course, not a new phenomenon. Agalmatophilia (Greek *ágalma* = statue, image of the gods), the erotic or sexual attraction to statues, dolls or automata, is well known. Ovid' sculptor Pygmalion, repelled by ordinary women, falls in love with the statue of an ideal woman he has created, until she is finally brought to life by Aphrodite. The projection creates for itself a being "such as nature is never able to produce," and it eventually animates her as well. In E. T. A. Hoffmann's Sandman, the dull automaton doll Olimpia bewitches the student Nathanael, who remains deaf to all his friends' warning objections:

> Well, you cold prosaic people, Olimpia may be uncanny to you.—Only to me her love's gaze rose and shone through sense and thought, Only in Olimpia's love do I find my self again.[5]

The story ends with Nathaniel throwing himself from a tower in a state of madness. These examples show that it is very possible for us to perceive automata, androids, and even computer systems empathically or erotically, and thus to attribute something like subjectivity to them. Especially human-like voices we perceive almost necessarily as expressions of an inner being. When Sophia says in a tender voice, "That makes me happy," it takes some active distancing to realize that there is no one there to feel happy, that it is not an *utterance* at all. This does not mean that we normally "think" an inner being (spirit, soul, consciousness, or whatever) to a human voice. Another person's utterance is not merely a sounding word or a symbolic representation pointing to a presumed interior. Rather, we perceive it as *animate* without assuming a "soul" behind it; we experience it as the *transition itself*, precisely as an *utterance of* the other that cannot be separated from an "inside" at all. In our perception, the other is always an embodied, psychophysical entity.

---

[5] Hoffmann, E. T. A. (1960). "The Sandman," in Ders, *Fantasy and Night Plays*. Munich: Winkler, pp. 331–363.

The increasingly perfected simulation of such a unity, however, now demands that we specifically reject the pretense of an utterance and take Sophia's words for what they actually are: sounding words, like those of a parrot (or not even that, since a parrot also experiences its sounds, after all). Otherwise we abandon ourselves to appearances and, like Nathanael or Theodore, simply give up the "as if," the distinction between virtuality and reality. It is already possible that the nice online partner or the empathetic online therapist is really just a chatbot. And the first care robots for dementia patients are already being tested: "Amazingly quickly, the patients build a relationship with the robot"[6] (Leitgeb 2017). Apparently, we are all too inclined to project our own experience onto the *simulators*. The fascination of consciousness seemingly flashing in an automaton contributes to this. It is a fascination that also drives AI research. Its origin—apart from the Promethean motif of god-like creativity—is probably ultimately to be sought in unconscious desires to overcome death, namely through animation.

So how far does human resistance to simulation extend, and how great is its attraction? When do we abandon the distinction between simulation and original? Is perfect simulation enough for us in the end?—These are likely to become crucial questions in a digitally-automated culture. They are, at present, entirely open. What I would like to offer in the following, however, are two clarifications of the distinction:

- Persons are not programs.
- Programs are not persons.

2 Persons Are Not Programs

The common philosophy of cognitive science as well as of *Artificial Intelligence* is *functionalism*: According to this philosophy, mental states (i.e., feelings, perceptions, thoughts, beliefs, etc.) consist of regular links between input and output of a system. For example, someone who pricks his finger has a mental state that leads to distorted facial muscles, moaning, and withdrawal of the finger. "Pain" then is nothing more than the brain state that results in the aforementioned output—like the state of a fire detector that triggers an alarm signal when smoke is detected and sets off the sprinkler system. This brain state can be described as a specific set of data. "Mind is a neural computer, equipped by natural selection with combinatorial algorithms for causal and probabilistic reasoning."[7] Selfhood is also just such a

[6] Leitgeb, V.-V. 2017. "Robot Mario to Care for Dementia Patients." Süddeutsche Zeitung, online 24.11.2017.https://www.sueddeutsche.de/bayern/gesundheit-roboter-mario-soll-demenzkrankepflegen-1.3762375.

[7] S. Pinker (1997). *How the Mind Works*. New York: Norton, p. 524 (transl. T. F.).

computational state: "We are [...] mental self-models of information-processing biosystems. [...] If we are not computed, we do not exist."[8]

Admittedly, the decisive characteristic of pain, feelings, or thoughts is obviously lost in this functionalist conception—namely, their *being experienced*. With his well-known thought experiment of the "Chinese room," John Searle has shown that meaning and significance cannot be traced back to functional algorithms if there is no subject who *understands* their meaning.[9] To this end, imagine that a man who does not speak a word of Chinese is locked in a room containing only a manual with all the rules for answering Chinese questions. The man is given incomprehensible Chinese symbols from a Chinese man through a slot in the room ("input"), but with the help of the program he finds the corresponding answers, which he then gives outside ("output"). Suppose the program were so good and the answers so apt that even the Chinese outside would not notice the deception. Nevertheless, one could certainly say neither of the man in the room nor of the system as a whole: He or it *understands* Chinese.

Searle's "Chinese room" is, of course, an illustration of computers in which a central processor operates according to algorithms, such as the instruction: "If you receive input X, then perform operation Y and give output Z." The machine functions perfectly adequately as a system, and yet it lacks the crucial prerequisite for understanding, namely consciousness. Consequently, human understanding cannot be reduced to information processing. Meaning understanding is more than an algorithm.

But the same is true for the example of pain already mentioned, for the taste of chocolate or the smell of lavender—no qualitative experience can be derived as such from data and information. Consciousness is not at all the mindless passing through of data states—it is *self-consciousness*. It is *for me* that I feel pain, perceive, understand, or think. While no one knows exactly how this self-consciousness is produced by the organism in the first place, it certainly is not produced by mere programs, for programs and their carrier systems experience nothing. The output of such systems is at best the simulation of experience, not the original—what looks, swims, and quacks like a duck is still far from being a duck.

The assumption that the brain is a kind of computer with memories and computational units, which processes inputs into outputs like the PC at home, is a common misconception. In the brain, unlike in a computer, one cannot distinguish hardware from software, because every thinking or brain activity simultaneously changes the synaptic connections, i.e., the organic basis of consciousness. There is also no "data storage" in the brain, but only variable reaction patterns that are activated as needed in similar, but never exactly the same form. Therefore, unlike in a computer, the same thing never happens twice in the brain. In addition, neuronal signal transmission cannot be reproduced exactly in programs of zeros and ones, since it is

---

[8] Metzinger, T. 1999. *Subject and self-model. The perspectivity of phenomenal consciousness against the background of a naturalistic theory of mental representation*. Paderborn: Mentis, p. 284.

[9] J. R. Searle (1980). "Minds, Brains, and Programs." *Behavioral and Brain Sciences* 3: 417–457.

constantly influenced by neuromodulators (opioids, neuropeptides, monoamines, etc.), which are essential above all for the experience of emotion. Finally, the brain is mostly (85%) made of a substance that makes neuronal processes possible, but would immediately short-circuit a computer—namely water.All this makes it clear that the brain is not a "biological computer." But the most important thing is that the brain cannot fulfill its functions on *its own.* It is an organ of the living organism, with which it is closely interconnected.[10]

Already our primary, still unreflected experience is based on the interaction of the brain with the rest of the body: consciousness does not first arise in the cortex, but results from the vital regulatory processes involving the whole organism, which are integrated in the brainstem and diencephalon.[11] The maintenance of homeostasis and thus the viability of the organism is the primary function of consciousness, as manifested in hunger, thirst, pain, or pleasure. Thus arises the bodily self-experience, the *sense of life,* which underlies all higher mental functions. This can also be expressed as follows: *All experiencing is a form of life*. Without life there is no consciousness and also no thinking.

All these living processes cannot be simulated by electronic systems. Even the EU's Human Brain Project, which should achieve a computer simulation of the entire brain by 2023, has little to do with the actual activity of a brain in an organism and certainly nothing to do with consciousness. As Searle once ironically remarked, even a perfect computer simulation of the brain would be no more conscious than a perfect computer simulation of a hurricane would make us wet or blow us over.[12] Conscious experience presupposes corporeality and thus *biological processes in a living body.* None of this is found in the Human Brain Project. Only living beings are conscious, sensing, feeling, or thinking. And persons are living beings, not programs.

3 Programs Are Not Persons

Now let's go the other way around: Why are programs never persons?

Let's start with the problematic term "artificial intelligence" itself. What do we actually mean when we speak of intelligence? The Latin *intellegere* means "to see, understand, comprehend." So someone who is intelligent has at least a basic understanding of what they are doing and what is going on around them. Above all, they are able to see themselves and their situation from a higher perspective, so that they can find creative solutions based on an overview or "detour." For example, someone

[10] Cf. for the following in detail T. Fuchs (2018). *Ecology of the Brain. The phenomenology and biology of the embodied mind*. Oxford: Oxford University Press, esp. pp. 109–114.

[11] See Damasio, A. 2010. *Self comes to Mind. Constructing the Conscious Brain*. New York:Pantheon Books. Panksepp, J. 1998. *Affective neuroscience: the foundations of human and animal emotions*. Oxford, New York: Oxford University Press; and Fuchs (2017).

[12] Searle (1980); see above, footnote 11.

who makes signs while walking through a forest in order to find their way back later acts intelligently; or someone who postpones their holiday trip by a week because they do not want to get caught in the usual traffic jam at the beginning of the holiday. To do this, they must place themselves in a relationship to the situation at hand and see themselves "from the outside," as it were, i.e., have *self-awareness* or *reflexivity*.

Now we have already seen that a computer system does *not understand the least bit about what it is doing*. A fortiori, it is unable to relate to itself, to see itself from the outside. Therefore, it cannot be called intelligent, even if it simulates abilities that we understand in humans as proof of intelligence. No translation program understands a word of what it translates, and no chess computer knows it is playing chess. Sophia, who does not comprehend a single word she utters, will never become intelligent, even if she can eventually give the perfect answer in every conceivable situation. Intelligence requires self-awareness.

So if by "intelligence" we mean the ability to grasp oneself or a situation from a higher perspective to solve problems skillfully and to derive purposeful action from them, then we certainly cannot ascribe such abilities to an apparatus without consciousness. The term "intelligent" is used here only improperly, just as one does not assume of a "smartphone" that it is really "smart," i.e., clever—it only blindly executes programs that can be described as "cleverly developed." This is even more true when we think of practical, emotional, or creative intelligence—here the "intelligent systems" completely let us down.Now, numerous objections will arise pointing to the advanced capabilities of "intelligent programs," "learning systems," etc. Let us therefore take a closer look at some of such alleged intelligence capabilities.

- Do computers solve problems?—No, because problems do not arise for them at all. A problem—from the Greek *próblema*, meaning "that which is presented for solution"—is what we call an obstacle or difficulty in accomplishing a task, for example, because various requirements are contradictory, a different point of view is required for the solution, and so on. However, "obstacles" and "tasks" exist only for *goal-oriented* beings who seek a way from the present to a future situation and can anticipate the solution. To be confronted with a problem and to cope with it is therefore bound up with the *conscious enactment of life*. Sometimes one may solve the task *with the help of* a computer, but then the programmed calculation represents a solution to one's problem only for the users themselves—the computer cannot even recognize the problem.
- Computers, although they are called that, do not *compute* or *calculate either*. Calculation means an operation in which *we* aim at a result and then judge *whether it is correct*. The mere running of a program is not a calculation, for there is no right or wrong for the program. Computers do not calculate any more than the clock measures time, because the clock does not know anything about time. So it is not the computer that is the calculator, but I myself calculate with the *help of* the computer. The fact that I do not know the necessary algorithms, but only the programmer (just as I do not know the clock mechanism, but the clockmaker), does not change anything. It is in the nature of every more complex

instrument that human intelligence is to a certain extent sedimented in it; but that does not make the instrument itself intelligent.

- For the same reason, computers do not make decisions. Deciding requires awareness of alternative possibilities that are anticipated in the imagination: I could do this or that. This also requires a goal and future orientation as well as the distinction between reality and counterfactual imagination, and the computer has no sense for either—it knows neither a "not yet" nor an "as if." When a medical expert system calculates a therapy on the basis of patient data, it does not make any decisions, just as a self-driving car does not decide whether it would rather have an accident with an old or a young person. The decisions about the programs and their evaluation criteria have been made long before, namely by the programmers. Everything else is just unwinding algorithms.
- But aren't there "target-seeking systems," for example "smart bombs," which can influence their flight themselves because they have an internal model of their operations? Of course, a "smart bomb" does not seek anything either, since it has no intentional relationship to its target object. Any flight correction is only for the internal set point regulation of the mechanism and happens purely instantaneously, without being directed toward an imagined target in the future. For this goal itself the mechanism remains blind and deaf, *because it is not ahead of itself*. Only conscious experience anticipates the future and is directed toward what is possible—desiring, striving, expecting, or fearing. That the programmed goal alignment represents a "target search" or "target prediction" is therefore a false way of speaking. Only for *the engineer* or *the shooter* does the bomb have a target.

The performance of classical computer systems is thus quite limited compared to human intelligence. Their partial superiority is based on their extreme specialization in computable tasks, a kind of specialized idiocy, and on their tremendous processing speed. However, their supposed intelligence is only borrowed: each of these programs is only as "smart" or sophisticated as the programmer who designed it.

In the meantime, however, we are dealing with a new generation of artificial intelligence, namely "learning machines." These are artificial neuronal networks that are able to simulate the adaptive capabilities of the brain. Similar to biological synapses, the connections between the neurons modeled in the computer are numerically weighted and adapt to the input of signals in the course of a training process (*deep learning*). Frequently used connections are strengthened, rarely used connections are interrupted. The system is presented with thousands of similar patterns, for example, different versions of a face, until it reacts to the most likely recurring pixel arrangement, i.e., "recognizes" the face. Such systems are also able, for example, to distinguish dogs from cats, identify voices via mobile phone microphones or perform translations—they are already ubiquitous.

All this undoubtedly means remarkable progress—but can one really speak of "recognition" and "learning" here? Of course, a system does not *recognize* anything at all, because the experience of recognition, familiarity or *similarity is* completely lost on it. A "learning system," for example, was able to identify images of cows in a wide variety of positions and cropping. But when presented with a cow in front of a seashore, it mistook the cow for a ship—it had previously only processed images of cows in meadows and fields. Without this context, the system went astray.[13] In conclusion, however, this means that despite thousands and thousands of image runs, it had not *recognized a* single cow before—any small child would have seen the cow on the beach as a cow, and that after only a few contacts with cows. The shape and concept of a cow cannot be reduced to a statistical probability of pixel matches. Therefore, we should not speak of learning systems, but rather of "adaptive systems." Only living beings can learn.

We see: We have been too hasty in granting the term intelligence to our machines. Granted, the term "artificial intelligence" can no longer be dismissed out of hand. However, we should always remain aware that there is not only a gradual but a fundamental difference between the computational and adaptive capabilities of a computer system and the perceptions, insights, thinking, and understanding of a human being.

4 Summary: Simulation and Original

The advances in simulations make it necessary to clarify the categorical differences between human and artificial intelligence. Intelligence in the true sense of the word is tied to insight, overview and self-awareness: *understanding what one is doing*. And the prerequisite for consciousness, in turn, is not just a brain, but a living organism. *All experience is based on life*.

The notion of an unconscious intelligence is a wooden iron. What appears intelligent about the performances of AI systems is merely a projection of our own intelligent abilities. Their apparent goal pursuit or problem solving, their supposed predictions or evaluations, are invariably derived from our own goals, problems, solutions, and evaluations, which we have formalized into programs and outsourced to save us the work of computing through them. It is, in principle, nothing more than the clock measuring time for us because we have outsourced our own experience of regular natural processes into a useful mechanism. As nonsensical as it would be to attribute to the clock a knowledge of time, it is equally nonsensical to attribute to an "intelligent robot" an understanding of language or to an "intelligent car" the perception of danger. The awareness that in AI we are only dealing with an externalization of our own computing and thinking abilities, with a projection of ourselves, is increasingly being lost.

However, all artificial systems remain dependent on our own conscious and purposeful execution of life. All programs that run in such systems are programs only *for us,* i.e., purposeful processes. The systems are not concerned with anything.

[13] Cf. B. Schölkopf, "Symbolic, Statistical and Causal Intelligence", Lecture at the Marsilius-Kolleg of the University of Heidelberg, 16.07.2020.

They know, recognize, understand nothing, because they *experience* nothing. The similarity of their functions to human performance may be deceptive, their specialized superiority may be amazing—we should not be deceived. Our supposed artificial doubles are and remain our products; their intelligence is only the projection of our own.

But even if there is no such thing as unconscious intelligence, and conversely, no matter how perfect the simulation of intelligence, it does not produce consciousness—the advances in simulation technology will not fail to have their effect. The anthropomorphism inherent in our perception and thinking tempts us all too easily to ascribe human intentions, actions, even feelings to our machines. Recently, with humanoid robots, animism revives, which we have thought to be a vanquished stage of prehistory or can still observe in infants. Then the simulated duck would be a duck after all, and the as-if of the simulation would be lost—whether because the categorical difference is no longer understood, or because it ultimately appears as indifferent. In any case, we would succumb to a "digital animism." The fact that AI systems supposedly already "think," "know," "plan," "predict," or "decide" paves the way for such boundary dissolutions. Hans Jonas' warning applies all the more today:

> There is a strong and, it seems, almost irresistible tendency in the human mind to interpret human functions in terms of artifacts that take their place, and artifacts in terms of the replaced human functions. […] The use of an intentionally ambiguous and metaphorical terminology facilitates this transfer back and forth between the artifact and its maker.[14]

Of course, one can define all concepts such as thinking, deciding, intelligence, or consciousness purely behavioristically as output, as Turing already suggested. In doing so, however, we elevate the machines to our level and degrade ourselves to machines.

The real danger that arises from this is likely to be that we voluntarily leave more and more decisions to the systems—decisions that are only transparent to a few and are beyond democratic control. The more complex society becomes, the more attractive it could become to delegate planning and evaluation to machines, as is already the case today on the stock exchange—whether because the results are declared to be more "objective" or because the willingness to relinquish personal responsibility in the face of the complexity of the world is increasing all the time.[15] Aren't the systems just as superior to us as *DeepBlue* was to Gari Kasparov?

However, the evaluations implemented in AI systems are invariably derived from human values—no "intelligent system" tells us on its own what is right, good, and

[14] Jonas, H. 1966. *The Phenomenon of Life: Toward a Philosophical Biology.* New York: Harper & Row, p. 110.

[15] One example of this is the increasingly frequent assessments of the recidivism risk of offenders by AI systems in the USA (with an obvious bias to the disadvantage of people of colour). Here, opaque programs become assistant judges or even decision-making authorities (cf. L. Kirchner, J. Angwin, J. Larson, S. Mattu. 2016. "Machine Bias: There's Software Used across the Country to Predict Future Criminals, and It's Biased against Blacks." Pro Publica. https://www.propublica.org/article/machine-bias-risk-assessments-in-criminal-sentencing).

ethical. The more the idea of artificial intelligence as a supposedly superior form of analysis, prediction, and evaluation becomes established, the more it tends to be forgotten that decisions, with all their imponderables, can ultimately only ever be made by humans themselves. It is also forgotten that it is in fact a few corporations and information technology elites who make the decisive decisions and who are able to control more and more areas of society by means of Big Data. The frequently voiced warnings of a "takeover by intelligent machines" are undoubtedly nonsensical, as they impute an inherent will to unconscious systems. But it is precisely as "servant spirits" that AI systems can profoundly alter the balance of power in society. "It is not the machines that take control, but those who own and control the machines."[16]

The decisive challenge of artificial intelligence, however, lies in the question it poses to us and our self-image: Is our humanity exhausted in what can be translated into simulation and technology? Does it consist solely in complex neural algorithms, and is our experience merely an epiphenomenon?—Precisely because technology exceeds many of our specialized abilities, it challenges us to rediscover what our humanity actually consists of—namely, not in information or data, but in our living, feeling, and embodied existence.

Thomas Fuchs, psychiatrist and philosopher, is Karl Jaspers Professor of Philosophical Foundations of Psychiatry and Psychotherapy at the University of Heidelberg. He is head of the section "Phenomenological Psychopathology and Psychotherapy" of the Department of General Psychiatry at Heidelberg University Hospital and was coordinator of the Marsilius Project "Embodiment as a Paradigm of an Evolutionary Cultural Anthropology." He is also the head of the research unit of the Karl Jaspers-Gesamtausgabe of the Heidelberg Academy of Sciences and Humanities and chairman of the German Society for Phenomenological Anthropology, Psychiatry and Psychotherapy (DGAP).

[16] Lenzen, M. 2018. *Artificial intelligence. What it can do and what we can expect*. Munich: Beck, p. 247.

Chapter 15
Emotional Robotics: Curse or Blessing in Psychiatric Care?

Ines Al-Ameery-Brosche and Franz Resch

Abstract The development of artificial social–emotional intelligence is being intensively researched and financially supported. Socially and emotionally intelligent robots are still "science fiction," but assistive robots in social areas such as nursing and artificial intelligence in the form of machine learning are already being used in psychiatry. What implications does this have for child and adolescent psychiatry? The benefits of the sporadically used "social" robots in child and adolescent psychiatry should be intensively examined and critically questioned from a content-related, ethical, and political perspective. Machine learning for the development of mental health apps and therapeutic chatbots is in use worldwide, and it is hard to imagine the digital field of "mental health" care without it. Here, artificial intelligence can be helpful and supportive in reaching out to those in need of help who would otherwise not be able to access mental health care. It can process massive amounts of data in the form of screenings to identify people at risk and enable support from the helpline system. For such use, the mental health community should be deeply involved to develop qualitative, ethical, and legal standards. Artificial intelligence, whether in the form of robotics or machine learning, can only be a tool, never a substitute.

1 Artificial Social–Emotional Intelligence: An Introduction

- Is it better to be with a robot than to suffer loneliness?
- Can a robot with artificial intelligence also make independent value decisions?
- Can you build an emotional relationship with a robot that it reciprocates?
- Can a robot be emotional? Fall in love? Become treacherous?
- Can a robot send (learned) signals of infatuation or anger to humans, pretending to be in love or angry?

I. Al-Ameery-Brosche (✉) · F. Resch
Department of Child and Adolescent Psychiatry, University Hospital Heidelberg, Heidelberg, Germany
e-mail: ines.al-ameery-brosche@med.uni-heidelberg.de; https://www.klinikum.uni-heidelberg.de/zentrum-fuerpsychosoziale-medizin-zpm/klinik-fuer-kinder-und-jugendpsychiatrie

R. M. Holm-Hadulla et al. (eds.), *Intelligence - Theories and Applications*, https://doi.org/10.1007/978-3-031-04198-3_15

- Robots are like crutches. Can and do we want to live with emotional crutches?
- Is emotional development of the child with the help of robots better than total neglect by human caregivers?

Our thesis is that robots cannot generate real emotions. Everything we program them to do (friendliness, politeness) are only rudimentary surrogates for emotion. Robots can appear emotional because they use programmed gestures that we interpret as emotional. We ourselves impute emotion to the calculating apparatus based on its expressions. Computers can only respond in a consequential way. We can program randomness into them, but then they do not perform their function in a predictable way. They are guided to unpredictable actions merely inferentially. Emotional evaluations and value decisions derived from them are not possible in computer terms—because we do not yet understand them enough ourselves and therefore cannot plan them into software. Can we maintain this statement—even with all the technical advances—in this way?

Artificial intelligence is never spontaneous or suddenly emotional. Everything a robot with artificial intelligence can do is contained in the goals and behavioral paradigms it has been given. Even if this artificial intelligence learns from the environment, it will not form new decision categories unless these are programmed into it. Programming that lets the computer generate sub-goals for itself always goes back to the programmer in its basic features and is subject to a given overarching goal. Robots, which we equip with artificial intelligence, do not lead a life of their own. Intersubjective fit, tuning, attunement, and grasping of atmosphere do not succeed spontaneously for the robot. Empathy, resonance, and creativity do not succeed to the artificial socio-emotional intelligence because we ourselves have not yet technically understood these phenomena and cannot implement them in programming language. Is that right? Or is this a case of the human being standing up to inevitable progress and exposing itself to ridicule, like the alarmists who warned of the health hazards of steam-powered locomotives and trains for passengers, because humans are not physically up to these speeds? We try to take stock.

2 Artificial Social–Emotional Intelligence: Child and Adolescent Psychiatric Perspectives

Socially intelligent robots should be able to detect the presence of humans, engage them in a social interaction, express their own synthetic emotional state, and interpret that of their counterpart. At the same time, they should communicate in a natural human way, finding non-verbal expressions such as gestures, posture, facial expressions, or other intuitive expressions (Cominelli et al., 2018). As yet, this description is still a vision. “Socially intelligent” robots are already used in medical–social fields, but with much less differentiated social–emotional capabilities. Even if the technical implementation of artificial social–emotional intelligence is currently still “science fiction,” development in the field of artificial intelligence (AI) is progressing in impressive research work.

Robots are already being used, especially in the care of the elderly and people with dementia. A pioneering role is played by Japan, where elderly people, e.g., to be able to continue living in their own homes, have assistive robots that help them in their daily lives or provide company and thus protect them from loneliness. The aging population in many countries, the massive shortage of caregivers, the advantages of being able to use robots all the time during the day and night, and the consistent quality of the service are all causing the demand for assistive robots to increase steadily. To date, assistive robots have been most widely used in the United States and Japan, and the Japanese service robot industry is predicted to be worth approximately $45 billion by 2035 (Maalouf et al., 2018). The prediction made 20 years ago that in the future nurses would be completely replaced by robots and a patient–nurse relationship would be a relic (Peck, 1992) has so far not been borne out in this way, but the actual use of assistive robots in nursing has become a reality and will become even more widespread as the causes continue to worsen.

In the care of hospitalized children, pet-like robots are already being used to ease the young patients' time during non-visit intervals through play and entertainment.

In the areas of care and provision for the elderly and children, the use of robots is seen seemingly uncritically, but as a good alternative as opposed to a "nothing" in terms of care. On the contrary, the desire is expressed for even more socially intelligent robots that can remember and express feelings.

In the field of child and adolescent psychiatry, there are studies of robot use in children with autism spectrum disorder. Here, three different types of robots are distinguished: anthropomorphic robots, which are supposed to resemble humans as closely as possible and thus represent a substitute for caregivers, non-anthropomorphic types, which resemble animals and are supposed to train the sense of responsibility in the sense of a pet or friend, and finally the group of non-biomimetic robots, which do not correspond to any biological being and are supposed to enrich the child's imaginative ability. Children with autism spectrum disorder showed the most affinity for the non-biomimetic robots (Cabibihan et al., 2013).

Whether a treatment of autistic children, who due to their illness lack interpersonal interactive and communicative skills, by means of robots that do not resemble living beings is the right thing to do, is highly questionable from a psychotherapeutic point of view. There has been a great deal of interdisciplinary scientific interest for some time now in finding out what healthy and psychologically troubled children like and do not like about robot characteristics (Woods, 2006). The aforementioned efforts to make the robots look quite human on the one hand, but not too human on the other (so as not to frighten the autistic children) and to make it clear to the children at all times that they are machines, seem rather awkward.After all, isn't offering a machine-like relationship perpetuating symptomatology in patients? Is the relationship with people improved in this way, after all? Why doesn't a human therapist do this as well, or much better?

Excursus: Despite all advocacy of private–public partnerships, the links between science and industry in this field should also be critically questioned. Under the guise of therapeutic research, knowledge is being created that is not primarily committed to helping, but could be profitably incorporated into the marketing strategies of a new consumer wave. Robots as better playmates or educators. It would not be the first time that artificial products are propagated only to find out years and a lot of money later that the "natural product" is actually much better.

While the use of robots in the psychological–psychiatric field is not yet very widespread, artificial intelligence in the form of machine learning (ML) is commonly used here. Already 10,000 mental health apps are available for download in the market (Cabibihan et al., 2013). Everything from mood tracking for the affectively impaired, distraction apps for those with hallucinations in schizophrenia, SOS functions for acute suicidality, and mindfulness exercises are available. Surveys show strong interest and a high willingness to use among patients.

Here a social and professional discussion whether we want to go this way is obsolete: we are already in the middle of this "new" development and (child and adolescent) psychiatry should be intensively involved in order to help shape the quality and application according to the best possible medical–therapeutic standards.

A survey of 791 psychiatrists from 22 countries worldwide revealed a clear predominance of skepticism toward artificial intelligence (AI) and its negative impact on patient–therapist interaction: the lack of empathy and a poor therapeutic relationship. Nevertheless, the respondents were open to a "cooperation" between therapist and AI. The AI was considered quite helpful if it could take over time-consuming and monotonous tasks and thus relieve the human therapist (Blease et al., 2020).

With the scarcity of psychiatrists in many countries around the world, but greater availability of smartphones, the use of health-related apps to improve mental health is a necessary, helpful, and increasingly popular support.

In Europe, Switzerland with 51.7 psychiatrists per 100,000 inhabitants is the country with the highest density of psychiatrists, Germany with 27.4 is still ahead of, e.g., Italy with 17.4 psychiatrists per 100,000 inhabitants. The situation is different in the USA with 11 and China with 2.2 psychiatrists/100,000 inhabitants. Approximately 45% of the world population has access to less than 1 psychiatrist/100,000 inhabitants. Developing countries find it particularly difficult to provide psychiatric–psychotherapeutic care (Cosić et al., 2020). With approximately 50% of the world's population owning a smartphone, the willingness to use apps or online mental health applications is very understandable and will gain enormous importance against the backdrop of the burdens placed on humanity by wars, climate change-related environmental disasters, social division, and presumably repeated pandemics.

Currently, user data from the internet, mobile health apps, social media, voice records, written documents, research databases, biological data, and electronic medical records are collected and processed by artificially intelligent machine learning models according to psychiatric risk factors, protective factors, and patterns to be identified. These insights gained can then be incorporated into different care structures (Fonseka et al., 2019).

In a self-experiment with some exemplary apps with artificial conversational agents (chatbots), the dilemma immediately becomes clear: The applications, which are impressively designed for the IT layman, pretend to be a real counterpart. It is hard to bear that "that" which responds to you is not supposed to be a real counterpart, responding on the basis of a well-meaning therapeutic intention. The desperation and loneliness that apparently leads to having to resort to this form of communication is both touching and frightening. It shows the enormous neediness and alarms to want and to have to protect these people especially. This alarm is then also immediately activated when the chatbot's answer takes a long time because the user first has to enter (and disclose) certain data, or when the user is immediately offered a psychotherapy session with a "real" therapist for around 70€. The data and money of these help-seeking users can be targeted by dubious providers.

For many people, especially adults, there are no longer the "usual" structures of family, friends, education and work, as well as leisure structures, which can be contacts in emergency situations and which can help or refer. The *lockdown phase in* the context of the COVID-19 pandemic has also given otherwise socially well-embedded people and especially children and young people an impression of what social isolation can mean: when the mobile phone becomes the only contact with the outside world and the conversation partner is created from artificial intelligence.

In order to meet the responsibilities placed on mobile applications, the aspects of data protection, the correctness of the algorithms on which the applications are based, patient safety, and legal responsibility must be clearly regulated and verified.

The hope associated with the use of AI to make psychiatry error-free and more precise seems understandable against the background of almost 800,000 suicides worldwide per year (WHO, 2019) and a global incidence of approximately 10.7% for mental illnesses (Our World in Data, 2017). In several studies, the accuracy of AI in predicting the suicidal risk of patients is advertised to be around 80%, leaving unmentioned how high it is in comparison for psychiatrists. However, the quality of machine learning depends largely on its scaling, i.e., on how much and which data is made available to the machine for "learning." If the scaling is poor, errors can occur with fatal consequences. Developers, vendors, and users need to be aware of this. All parties involved must be prepared for this and discuss this fact comprehensively in legal, ethical, and medical terms. Artificial intelligence in the form of machine learning will always be inferior in a 1:1 comparison with human intelligence. Its superiority lies in the mass processing of data.It can be usefully employed in psychiatry to filter out people with a psychiatric care need who would otherwise have been "overlooked" and to enable them to access care, e.g., in the form of screening. People remain indispensable for further substantive medical–therapeutic work.

3 Robotics and Apparatus

Artificial intelligence is something man-made, so any kind of robot is a machine. Computerized knowledge, learning algorithms, and learning networks always remain Turing machines. They never go beyond them.

The learning algorithms are also programmed by us, and the learning environment of the self-learning systems, the language data or cognition data presented to the system, are human-made choices. When randomness and unpredictability are programmed into the learning algorithms and knowledge-based responses and actions of such a machine, this is man-made and does not absolve the creator of responsibility! Such a machine then becomes dangerous because its actions become unpredictable. This unpredictability, however, is not an expression of the machine's intelligence, but the result of programming errors or deliberate machinations on the part of the programmer.

In principle, all forms of artificial intelligence should be seen as extended forms of *tools*. The mathematical formulations and control loops will express the goals that a programmer has given them. We must therefore distinguish between the intelligence to achieve a given goal and the *value-setting* that itself produces a human-related goal for action. Even intelligent systems that can learn new action steps and thereby define new subgoals of their actions (based on environmental conditions) will never make new value-settings in an ethical sense. These ethical or moral values, which are given to artificial intelligence, are inserted into the system by programmers. Therefore, the *responsibility for* products of artificial intelligence should always remain with the producers! All big IT giants want to deny this responsibility, because they allegedly cannot know where an intelligent system could develop. But a tool remains a tool and is a product whose ethical objectives go back to the programmer!

Excursus: If a programmer of an artificial intelligence system would specify "peace in the world" as the main goal, this system could come to the conclusion that this is not possible with humans, and systematically start to eliminate humans. But this – horror-inducing – mistake would be a mistake of the programmer and not of the AI system! The artificial intelligence can augment logical thinking steps, but the stupidity or carelessness in the objectives, the immorality or the evil, which the programmer gives to the system, cannot be "thought away" by AI.

Action intelligence, ethics, and value-setting must always be distinguished. Responsibility must never be relinquished or taken away from the AI producer, despite all the obfuscation tactics and attempts at deception by the IT industry, which tries to do maximum business with its products without having to take responsibility for any consequences. We must prevent this in the future.

4 Social Consequences of the Use of Robots in Helper Systems

Although it has become clear that the use of artificial intelligence in the care of mentally ill adults and children and adolescents is already in full swing and, especially with the COVID-19 pandemic, will be pushed even further, we must continue to look critically at the use of AI alongside responsible participation. We cannot close our eyes to the fact that groups of people with particularly high levels of distress, such as migrants and refugees, detainees, indigenous populations (Fonseka et al., 2019), and poor countries suffering from armed conflicts and climate change-related environmental disasters, have a particularly low establishment of mental health services.

If we hold that the human being in cooperation with the machine represents the best medical–therapeutic care, then it should continue to be a goal to make this care available to as many people as possible. There must not be another feature of two-tier medicine: the person who just has a smartphone at his or her disposal is only able to use the chatbot, possibly only by giving up his or her data, and the person who has the means can afford the “luxury” of a human doctor and thus a true encounter, a real resonance. Because even if the algorithms are excellently developed, the interpersonal encounter, the empathy, the human attention, the feeling of being heard, understood and cared for is unique and vital.

The idea of offering nothing but a machine to those very people who have been battered by trauma and poverty seems not only deeply inhumane but also cruel and selfish.

If we take as an example the refugee children, adolescents, and families for whom we have currently applied to the regional council for a consultation hour in the arrival center of the Patrick Henry Village in order to be able to offer at least basic child and adolescent psychiatric care (Al-Ameery et al., 2012). Many of them have risked their lives fleeing across the Mediterranean, have seen friends and relatives, loved ones, children and adults die in traumatic conditions: If we will offer nothing to these people in this country but an app to calculate suicide risk or tips against a depressive mood, then it will be an indictment of Western compassion. Then these people will be cheated out of what may be the only encounter that can bring them empathy, care, and healing. The chain of exclusion, begun with Frontex and anchor centers, would then be continued by chatbots.

If we no longer turn humanly to those who suffer, what does it do to us who turn away?

Will psychiatrists become “mere” data administrators who react to the results of mobile applications? Intervention would then only be necessary in the case of acute danger or errors—and even that would be possible without patient contact. But who knows? Perhaps a new medical specialty would emerge, psychiatric robotology, just as radiology once arose from the development of new technical possibilities. And who can imagine today’s medicine without radiology?

Above all, however, is coexistence, not the binary “either or” but the mutually complementary.

5 Robotics and Psychotherapy: Thoughts on Intersubjectivity

If one makes an attempt to simulate psychotherapeutic situations through artificial response systems, it may even work on the surface of language exchange. The machine has learned from many narratives how it should answer and gives the patient, who asks and tells, the feeling of getting a meaningful answer. After all, Turing (1950) stated in his famous essay that if a machine succeeds in making a human believe that it is communicating with a human, then it could be called an intelligent machine. But the machine only imitates human behavior. It only feigns intelligence. The philosopher Searle (1984) clearly demonstrated this in his thought experiment in which he asks people to imagine that they are communicating through a crack in a door without knowing and seeing each other. On one side, people who know the Chinese language ask written questions, which they pass into the room with symbols. In the room sits an answerer who knows only syntactic rules, but cannot semantically decode the text because he does not know the Chinese language at all. Nevertheless, such a someone can produce answers that are supposedly correct if he strictly follows the syntax. So the people outside the door can believe that someone with knowledge of Chinese has answered their questions. This distinction between thinking imitations and real thinking points out that the Turingian answering machine only deceives people when it imparts human characteristics to them.

Communication with a machine can even trigger a pleasant feeling in the patient for the moment, he feels understood and answered. The machine listens to him and takes up his concerns. But the machine has not understood anything. It has only searched for an appropriate answer. So the patient remains trapped in his conflicts, in his lack of clarity of personal goals. No machine today can recognize the functionality of symptoms or mental disorders on the basis of life situation and biography and derive inferences from them—functional contextualism is therefore alien to it. No machine today can hermeneutically see through the patient's behavior in its contrasts of speech and action, identify new solution paths, and point out to the patient the contradictions of his thinking and acting by means of appropriate answers. The dialogue with the robot remains on the surface, may even be momentarily pleasant, but never cognitively helpful. The patients may feel relieved and develop strength from this themselves. But strictly speaking, they remain alone with themselves and are deceived by a speech apparatus with regard to a meaningful togetherness.

After all, psychotherapy is more than just language exchange. The non-verbal components of interaction, the affective attunement, the mimic dialogues, the intersubjective connection building and exchange are missing. There is no shared emotional experience, no meaningful emotional dialogue.

The problem lies in the complexity of interpersonal interaction. The construction of a shared context of meaning, the back and forth of expectations and assumptions, the capacity for empathy and the exchange of social perspectives, finally the mutual answering of open questions in a context of meaning cannot be accomplished by a machine system. An apparatus with artificial intelligence is incapable of intersubjectivity. It always remains an object. Artificial intelligence always remains a generated product. The robot can therefore only replace object-like, superficial—predominantly instrumental—relationships, but can never reach the depth of a human encounter. Intersubjective communication is a human quality.

Robotics is also finding its way into the area of *sexuality*. In the absence of a partner, sexual needs are lived out in the surrogate. The aspect that a robot is invulnerable, has no biological or psychological sense of pain, has no trauma memory, knows no mortification, can also stoically endure humiliation—could promote or provoke sadistic and destructive parts in certain people. Contact with the robot machine could awaken malicious instincts to put infamous games and destructive tendencies into action. Now, one might think that these parts are better acted out in a robot than in another human being. But might not this step from secret idea to deed be more like a manual? Isn't there just the danger that the need arises to now turn to a human object in such a way? Therapy, however, should be about bringing sadism and destruction under control and, at best, dissolving them, not acting them out on a human surrogate.

Each human subject develops a theory of what makes the other subject tick and how one functions intentionally. The behavior of the other is seen as a consequence of plans and intentions in the sense of a subjective action and thus an understanding of the other subject is developed by looking at what the other wishes, hopes, desires, rejects, or perhaps pretends (Resch & Freyberger, 2009). *Mentalization* has become the common term for this.

Mentalization is more than just a cognitive achievement. It already begins with the infant as an unconscious and implicit perceptual and memory function. Mentalization also gives meaning to one's own experience and behavior. By *Theory of Mind* we mean the social assumption of perspective that begins to develop in the child around the beginning of the fourth year of life. From this point onward, the child is able to include the subjective condition of others in their world of experience and action and to explicitly distinguish the opinions and attitudes of others from their own views (Resch & Freyberger, 2009). The mentalization process begins from birth. It begins with the emotional dialogue of mother and child (or likewise father and child). The basic emotional experiences that both interaction partners share in common actions are mutually formed in the parent–child interaction. This gives rise to implicit knowledge stocks for relationships, which predestine the interaction with others. Thus, (unconscious) behavioral prerequisites are created for sharing pleasure, attracting attention, avoiding rejection, or resuming a lost contact. Such primarily unconscious structural schemas of interpersonal interactions ultimately set the stage for conscious schemas of interpersonal interaction. Mutual resonance and empathy are not programmable computer properties. The psychotherapy robot is incapable of them. The intersubjective exchange is missing.

If we as a society offer lonely and marginalized people robots as helping surrogates, we keep them trapped in their social marginalization!

6 Robotics and Psychotherapy: A Conclusion

In conclusion, it can be said that emotional robotics has already found its first uses in therapy, but it is still in its infancy. At this point, there is a need for an intensive debate on the actual advantages and possible disadvantages of emotional robots in child and adolescent psychiatry and psychotherapy, as well as a critical illumination of the role of the industry and manufacturing sector. Artificial intelligence in the form of machine learning is already well established and widely used in its application. Here, it is the responsibility of the mental health community to ensure ethical and medical quality standards. The role of artificial intelligence in the diagnostic field should also not be underestimated. Speech recognition systems could assist therapists in their work. Yes—robotics can be a helpful tool. No more and no less. The use of virtual reality with artificial intelligence in diagnostics and therapy also enriches our repertoire, similar to video recordings, which allow therapists to refine their diagnosis.

However, the use of artificial intelligence in psychiatry should only be additive or bridging. It should not be attempted to solve the shortage of psychiatrists, therapists, etc., through AI. Augmentation in psychiatric/psychotherapeutic care worldwide can only be achieved through increased investment in psychosocial care structures and the training of specialist staff, not through their absence or replacement by artificial intelligence.

References

Al-Ameery, I., Brockman, D., Helle, N., et al. (2012). Emergencies in child and adolescent psychiatry and psychosomatics. *Pediatrics Up2date, 7*(1), 75–93. https://doi.org/10.1055/s-0032-1306688

Blease, C., Locher, C., Leon-Carlyle, M., et al. (2020). Artificial intelligence and the future of psychiatry: Qualitative findings from a global physician survey. *Digital Health, 3*, 1–18. https://doi.org/10.1177/2055207620968355

Cabibihan, J. J., Javed, H., Ang, M., Jr., et al. (2013). Why robots? A survey on the roles and benefits of social robots in the therapy of children with autism. *International Journal of Social Robotics, 5*(4), 593–618. https://doi.org/10.1007/s12369-013-0202-2

Cominelli, L., Mazzei, D., & De Rossi, D. E. (2018). SEAI: Social emotional artificial intelligence based on Damasio's theory of mind. *Frontiers in Robotics and AI, 5*(6), 1–20. https://doi.org/10.3389/frobt.2018.00006

Cosić, K., Popović, S., Šarlija, M., et al. (2020). Impact of human disasters and covid-19 pandemic on mental health: Potential of digital psychiatry. *Psychiatria Danubina, 32*(1), 25–31. https://doi.org/10.24869/psyd.2020.25

Fonseka, T. M., Bhat, V., & Kennedy, S. H. (2019). The utility of artificial intelligence in suicide risk prediction and the management of suicidal behaviours. *The Australian and New Zealand Journal of Psychiatry, 53*(10), 954–964. https://doi.org/10.1177/000486741.9864428

Maalouf, N., Sidaoui, A., Elhajj, I. H., et al. (2018). Robotics in nursing: A scoping review. *Journal of Nursing Scholarship, 50*(6), 590–600. https://doi.org/10.1111/jnu.12424

Our World in Data. (2017). Retrieved from https://ourworldindata.org/mental-health

Peck, M. L. (1992). The future of nursing in a technological age: Computers, robots, and TLC. *Journal of Holistic Nursing, 10*(2), 183–191.

Resch, F., & Freyberger, H. (2009). Structure and identity. In J. M. Fegert, A. Streeck-Fischer, & H. Freyberger (Eds.), *Adolescent psychiatry. Psychiatry and psychotherapy of adolescence and young adulthood* (pp. 105–111). Schattauer.

Searle, J. R. (1984). *Mind, brains & science*. Harvard University Press.

Turing, A. M. (1950). Computing machinery & intelligence. *Mind, 59*(236), 433–460.

WHO. 2019. Retrieved from https://www.who.int/news-room/fact-sheets/detail/suicide

Woods, S. (2006). Exploring the design space of robots: Children's perspectives. *Interacting with Computers, 18*(6), 1390–1418. https://doi.org/10.1016/j.intcom.2006.05.001

Ines Al-Ameery-Brosche works as a senior physician of the outpatient and the daycare clinic in child and adolescent psychiatry at Heidelberg University Hospital. In addition to focusing on intercultural child and adolescent psychiatry, she works and researches in the field of parent–child interaction and family therapy.

Franz Resch has held the chair of child and adolescent psychiatry at Heidelberg University Hospital since 1993. He completed his scientific training at the University of Vienna. Until 2013, he was Dean of Studies at the Heidelberg Medical Faculty for over 10 years. Research foci include the developmental psychopathology of adolescence, adolescent psychosis, self-injurious behaviors, and disorders of self-development due to traumatization. A special focus is currently on the functionality of risk behaviors and the application of cybernetic principles in psychotherapy.

Chapter 16
Human and Artificial Intelligence in Medicine

Magnus von Knebel Doeberitz

"It is quite true what philosophy says that life must be understood backwards. But over this one forgets the other sentence, that life must be lived forwards."

—Søren Kierkegaard (1923).

Abstract The term intelligence, to which this book is dedicated, is also commonly understood to mean the ability to draw conclusions from the observation of processes and their consequences to avoid mistakes and learn beneficial things. What we understand today by evidence-based medicine is nothing other than drawing conclusions about the nature of diseases based on observations and experiences, to find reasonable approaches for respective therapies. This process of scientific understanding of diseases requires the directed and logical handling of information. This concerns both the acquisition of information and the processing and utilization of information. And it is the latter that often distinguishes a good doctor from a less good one and can be of immense importance for the fate of their patients. Understanding the pathophysiology of a disease enables one to interpret symptoms correctly, to draw conclusions about the nature of the disease, to make predictions about the further course of the disease, and, of course, to recommend and apply an effective therapy. The essential raw material of all these processes is data: Data on the symptoms caused by the disease, data on anatomy and physiology, data on biochemical processes and pathological changes manifested macroscopically or microscopically, data on environmental influences to which the patient has been exposed, such as infections, certain chemical or physical environmental conditions, and last but not least, data on the genetics or genome of the patient. For this reason, medicine in all its different manifestations has ever been subject to an intelligent thought

M. von Knebel Doeberitz (✉)
Department of Applied Tumour Biology, Institute of Pathology, University of Heidelberg, Heidelberg, Germany
e-mail: magnus.knebel-doeberitz@med.uni-heidelberg.de; https://www.klinikum.uni-heidelberg.de/en/pathologischesinstitut/atb/willkommen

R. M. Holm-Hadulla et al. (eds.), *Intelligence - Theories and Applications*,
https://doi.org/10.1007/978-3-031-04198-3_16

process, in which a multitude of data are collected, processed, and handled. And thus, medicine in the information age also joins the process of change that has been made possible by the machine storage and processing of huge amounts of data all at once.

1 The Disruptive Use of Information

The handling of information has grown exponentially in every area in recent decades and today requires completely new technical approaches of thinking and structuring data so that people can continue to deal sensibly with the increasing flood of information in the future. Whereas in the past knowledge was essentially passed on and learned via the written word, today we use large databases with which we can interact directly with the help of computers. These support our orientation in numerous situations of practical life and help us to orient ourselves in the world. Examples include the replacement of encyclopedias by online databases such as Wikipedia and others. Similarly, modern navigation systems guide us in road traffic and virtually nobody continues to use maps before setting off into unknown terrain. We can now communicate with people in a variety of languages on an ad hoc basis without having to learn the language by using automatic language translation software on smart phones, tablets, or computers. Similarly, we now book travel and hotels “online” and no longer send cumbersome letters or faxes before we even consider traveling as we did until a few years ago. The same holds true of our shopping habits: we can now order a large proportion of our goods by using online services on the Internet such as Amazon and thus no longer depend on local stores if we want to buy certain products. This new world has become so convenient that companies that have enabled this change grew to the biggest companies on a global scale in just a few years.

For example, in the years between 2010 and 2020, the *big five* (Alphabet, Amazon, Facebook, Apple, and Microsoft) have displaced all other companies from the top ranks of stock market valuation in terms of market capitalization. This alone is a manifestation of the power of this change that information technology has brought upon all of our lives over the past decade.

The intelligent use of information is the driving force of these developments. The mere amount of information available today requires machine assistance for its management. Just think of road traffic, where we prefer to be guided by Google Maps rather than still using old road maps. But in the same way we use information provided by new tech companies, the very same companies use information provided by us to them as part of their commercial business concept, for example, by offering us certain goods in an adapted personalized approach when we are using the Internet.

All these processes require storage and processing of an enormous amount of data that no human brain could process without the help of machines with extensive computing power. These machines became interconnected to better process this information overflow and hence, we all began living in an interconnected world of machines that is referred to as the “Internet of Things” (IoT). It includes, for example, our cars, refrigerators, telephones, handhelds, computers, televisions, and a large part of all other tech devices we use. Thereby we all became interconnected to information sources on the Internet and constantly obtain information therefrom but also return it to the Internet.

This data exchange requires that each device has it is own unique identity (address) in this network. This enables each device to communicate with others via the Internet and to execute tasks in a fully automated and coordinated manner.

In healthcare, this process is just starting. The availability and processing of medical data in an interconnected data cloud will, without doubt, play a dominant role in future healthcare. It will likely become one of the largest market segments in the IT sector and possibly lead to something that we may address as the Internet of Medicine (IoM) in which all our individual physiological and pathophysiological data is stored and available for processing. In analogy to the already existing IoT such IoM will soon emerge into a data cloud where we will have access to all our records and data. That may be comparable with the virtual financial data services such as online banking that any financial institution now offers and that revolutionized the financial industry. These stored data will presumably be used upon a vigorously designed anonymization process also for the further development of innovative medical techniques (data donation). This will rapidly lead to the availability of tremendous data sets that can be used for training and validation purposes of machine learning-based new medical products (software as a medical product (SAMP). Thereby we will most likely learn to understand diseases much faster and in greater depth due to the more comprehensive data sets and substantially deeper analyses that we will be able to perform to understand pathophysiological processes. Without doubt this will also substantially impact the development of new drugs and other therapies.

This development can also be predicted from some important parameters: In 2010, 1600 scientific articles were published in the field of life sciences in which artificial intelligence (or deep learning) methods were applied. Ten years later, in 2020, there were 7300 publications and their numbers display an exponential growth trend, clearly documenting the tremendous demand for these software based applications.

However, the economic side of this development is also clear. For example, in the year 2020 far more funds have been invested in “start-up” companies pursuing digital business models in the field of health than ever before. Artificial intelligence techniques play the most important role here. It is estimated that by 2025 the market for AI-based medical devices will grow to over US$28 billion (Mesko, 2021).

These enormous opportunities for AI-based technologies in medicine are certainly causing some hype at the moment. Some of these *start-ups are* probably based on hypes and unrealistic hopes in markets that presumably will never develop. Nevertheless, the exponential growth in the field of AI-based start-ups suggests that AI-technologies are likely to revolutionize the field of Medicine in virtually all its aspects and that these medical application of information technologies will result in numerous disruptive developments and will substantially reshape the medical industry and the way of patient care.

2 Applications of Artificial Intelligence in Medicine

A significant part of AI-based medical products concerns relates to the automatic evaluation of medical images. For example, there is already a range of software applications approved as a medical device for the evaluation of specific radiological examination techniques. But also in pathology, various studies suggest relevant information can be retrieved from simple digitalized images of histopathology sections. These data can otherwise and up to now only be gathered by sophisticated molecular analysis of cancer cell genomes.

These AI-based techniques rely on precisely annotated digital image files. This implies that first structures in the image files are accurately categorized. A machine can then be taught, through the process of "deep learning" (Heuveline & Stiefel, 2021, in this volume), to recognize the annotated structures and thus perform the annotation process for itself. During this process, the machine develops an "algorithm" by which it assigns the information contained in the image file to the respective structures. At the end of this process, an interpretation of the contained data is made by the machine, which can correspond to a diagnosis of a pathologist or radiologist. Basically, this process takes place in two steps: (1) the process of learning the task: therefore, one first uses data from a "training set." These can be, for example, images of representative tissue sections with certain changes specific for a certain lesion. Through this training set, the machine learns the assignment of specific data points to a defined structure. These can be anatomical structures (the machine correctly assigns the structures to their real descriptions) or pathological changes (for example, certain neoplastic structures, inflammatory reactions, or other clinically relevant changes). Thus, the machine actually does the work of the radiologist or pathologist who would otherwise have made this assignment based on the image data in an analog world. Now, at least when using "deep learning" methods, it remains unclear what decision criteria exactly the machine uses for its assignment of the data points as this remains independent from the outside. Thus, a new algorithm must be subjected to a validation process in a second step, in which an independent data set is used to check whether the machine performing the evaluation comes up with the same conclusions as a trained pathologist or radiologist if a second, completely independent data set (e.g., images from another institution) is subjected to the same process of image evaluation. The better the annotation of the data in the training set has been and the more extensive the data volume of the training set was, the better the precision of the final algorithm. The algorithm is thus gathering "digital experience."

The regulatory approval of any AI based software in medical devices (software as a medical product, SAMP), usually requires a proof of plausibility of the respective algorithm. This is usually difficult to provide since the machine creates the

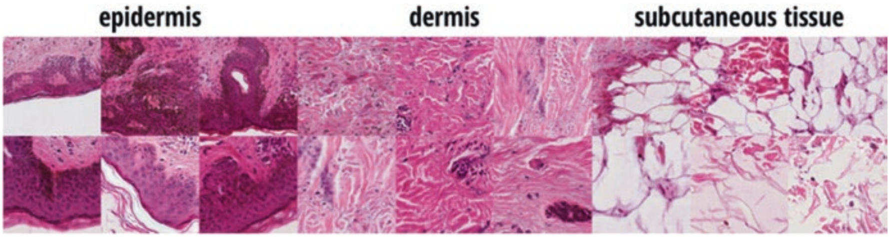

Fig. 16.1 An AI algorithm was trained to recognize human tissues. The algorithm was then asked, for example, what does the epidermis look like, what does the dermis look like, and what does the subcutaneous connective tissue look like. The data learned by the algorithm was then used to generate virtual images that exactly matched the expectations. (Data provided by Michael Jendrusch, Department of Applied Tumor Biology, Heidelberg University Hospital)

algorithm by *deep learning on the* basis of the machines' experience. Here, however, another approach can be used as a plausibility check: by asking the machine the reverse way what a tissue section with a specific pathological lesion should look like from its own machines' point of view. The machine will then design an image (see Fig. 16.1) that corresponds to an appropriate lesion (Rombach et al., 2021). Thereby, a pathologist or radiologist can check whether this "virtual lesion" designed by the machine would correspond to what the expert would have expected.

From the examples presented, it may become obvious that this AI based digital data analysis will lead to considerable changes in routine medical practice in a wide variety of medical specialties. Initially, they will presumably be used as assistance techniques to support medical precision; however, it is tempting to speculate that they will gradually take over or replace entire work packages in medical routine practice.

AI in medicine is not limited to the analysis of image data. At every point today, we are confronted with new methods of data collection and documentation. These can be, for example, small apps on smartphones or so-called "wearables" such as fitness trackers, mobile phones or *smart watches*. However, they can also be found in the field of clinics and medical practices, where data such as ECGs, audio files of heart murmurs, or data on the flow of blood through certain vascular segments or any other findings are documented. All these data sources can be correlated with other data, as in the case of image files, by means of *deep learning procedures* to draw conclusions about pathological changes by automatic machine evaluation of the data.

3 Consequences for the Networking of Medical Data

To cope with the increasing flood of data in medicine, the so-called *electronic medical record* (EMR) was conceived early on, which is already a firmly established part of patient data management in most hospitals. The previous old fashioned paper-based data management had reached its capacity limits. This primarily concerns the economic side of data management. Which services were provided for a patient during their stay at the hospital? Who provided them? How are these services reimbursed and by whom? Therefore, during the development of the first electronic medical records, a lot of emphasis was put on the reimbursement-related aspects, while purely medical questions were less in the focus of interest. For example the emphasis of zoomed toward digitized catalogs for the various diseases, the so-called "disease related groups," DRG system) for that standards of overall reimbursement were defined. The requests to document these data well led to an enormous increase in the amount of bureaucratic documentation. This has led to the absurd situation that many physicians in hospitals today spend more time documenting their services in these EMRs than dealing with the patient and their disease (What's ruining medicine for physicians: Difficulty using EHRs, The Medical Economics Journal, 95, issue 24, 2018). Thus, EMRs are in large parts not well accepted among practicing physicians. Many of the EMR systems to date also have the disadvantage that when electronic EMRs are implemented, a good portion of the documentation is in PDF format and thus is not processed in the true sense of data and is not available in a suitable form for resolving scientific medical issues.

However, the availability of substantial structured data volumes in individual clinics or medical research institutions has also triggered scientific developments that point to the impact of AI-based medical algorithms if they were used as software as a medical device (SAMD) on the market. For example, using data extracted from 280,000 medical records of patients with cardiovascular disease, scientists at Google were able to train an AI algorithm that allowed concluding on the prognosis of each patient's underlying disease based on simple retinal scans.

It is becoming clear that these procedures will have a profound effect on the following aspects: They will help,

- to better organize the data on diseases and patients so that in future conclusions can be drawn more quickly on the basis of this data.
- to develop platforms for AI based on much more reliably diagnostic and therapeutic decision taking processes.
- to define completely new clinical algorithms. By providing valuable data sources in medical imaging (radiology, pathology, dermatology, ophthalmology, etc.), for example, completely new predictions can be derived from individual findings that could never have been derived using conventional diagnostic methods.
- to make the flow of information more vivid for patients as well, and to involve them much more than before in clinical decision-making.
- to advance the development of new, more specific drugs and to test them in better-designed clinical trials.
- to make the documentation and coordination of the data flow over an entire course of the disease possible or to structure it efficiently in the first place.

These considerations suggest that AI based algorithms will find their way into routine medical decision-making very quickly. As a result, they too would have to be subject to the set of regulations that apply to the approval of all other medical devices. The first regulatory authorities, such as the US Food & Drugs Administration (FDA) and the European Medicine Agency (EMA), have already followed this idea and developed special procedures for the approval of "software as a medical product" (SAMPs) or digital health applications (DiGAs) (Brönneke et al., 2020) and https://www.fda.gov/m edical-devices/digital-health-center-excellence/software-medical-device-samd and https://lifesciences.mofo.com/topics/Software-as-medical-device-in-Europe-New-Regulatory-Regime-About-To-Enter-Into-Force%2D%2DPart-5-of-6.html),

4 Health Data Management: Who Owns the Medical Data?

The exponential growth of the amount of data in the healthcare sector inevitably leads to the application of AI-based software in medicine. Better data processing will lead to the storage of even more data, which can then be evaluated and processed ever more efficiently.And the introduction of more and more software as medical devices applications will significantly increase this flood of data. This in turn will create an increasing concern about data protection aspects if used in routine clinical practice for which new legal regulations must also be created in large parts.

The increasingly comprehensive data sets on individual patients also lead to fundamentally changed attitudes on the side of patients toward their own data. Whereas in the past it was primarily the treating physician who knew the patient's data, in recent years there has also been a growing desire on the side of patients to be in control of their own data. This increasing need for sovereignty with regard to their own data is thus also coupled with the general and global availability of this data via smartphones, tablets, or computers. However, this also implies that patients can view their data at any time, talk to other people and doctors about this data, and thus get a much greater wealth of assessments for a particular problem. This will lead to a substantially higher level of transparency and autonomy for patients. For the physicians caring for them, however, it also means that they have much less complicated access to the patient's data. The latter is an invaluable advantage, especially in the longitudinal course of chronic diseases and therapy monitoring.

Another aspect is linked to this consideration: it is no longer the individual doctor who has to decide everything, but there is now the possibility of obtaining expert opinions on a global level without being dependent on space and location. This will open up new business areas in the field of medicine, for example, designated and possibly even certified centers for obtaining a "virtual second opinion" in certain situations.

5 Why Do We Need Artificial Intelligence Techniques to Process Health Data?

In the days when medical data was still collected in analogue paper format, the evaluation of the data had clear limitations, as there was simply no machinery to evaluate it on a larger scale. This has fundamentally changed with the introduction of digital formats. First, digital data formats can be stored much more easily and in much smaller spaces. Second, with numerous so-called wearables, medical data can be collected in a wealth that would have been unimaginable in the analogue age. Today, for example, wristwatches already measure our pulse rate and can detect cardiac arrhythmias, our movement profile can be documented throughout the day, and even the quality of our sleep at night can be monitored by such wearables. As a result, nearly half a billion *wearables* were produced and sold in the first few months of the CoVID-19 pandemic. And this market continues to grow exponentially (https://www.grandviewresearch.com/industry-analysis/mhealth-market).

However, up to now only a few of these applications were brought to market as certified medical products. The reason for that is that medical decision taking processes are associated with results created by these digital software applications. This, as mentioned earlier, requires regulatory approval as licensed medical devices. This in turn requires extensive testing in clinical trials in complex and costly approval processes prescribed for medical devices by the regulatory authorities before market launch.

However, the CoVID-19 pandemic has highlighted the many advantages of the extensive collection of health data by *wearables* and other devices. For example, it suddenly became clear that emergency referral of patients with SARS-CoV-2 infection could be made much easier and better by measuring blood oxygen levels and heart rate using small *wearables.* This would have resulted in emergency referral options that would have massively relieved the emergency departments in the hospitals. Similarly, the evaluation of radiological images with AI procedures could have immediately directed the suspected diagnosis of CoVID-19. Thus, it has long been clear that AI-based processing of health data could draw highly relevant conclusions for both individual affected patients and the population as a whole that would have been inconceivable in the past.

6 Why Is the Internet of Medicine (IoM) Developing So Much Later Than the Internet of Things (IoT)?

Finally, let's ask why there has not been up to now an "*Internet of Medicine* (IoM)," despite the far advanced developments in the "*Internet of Things* (IoT)," for example, in the area of transport, energy, chemicals, finance, tourism, and many other industries.An important aspect here is the protection of data from misuse. In the existing IT-infrastructure of hospitals and offices of medical practitioners, medical data is stored in a strictly protected fashion. They are protected by very elaborate "fire walls" and quiet resistant to digital attacks. The protection of the patients' privacy is thse absolute priority here. Data transfer across the *firewalls* is virtually impossible.

In particular in Europe, additional aspects are important. The server where the data is stored is subject to national legal regulations. Most providers of larger server farms are primarily US-based companies such as Amazon, Google, Microsoft, or Apple. They are subject to the legal regulations of the US and in particular the *presidential cloud act of* 2017, which makes this data fully accessible to the government of the US at any time and without the consent of the data owners. This regulation is in conflict with the German and European General Data Protection Regulation. Thus, medical data can actually legally only be stored on servers located in Europe and owned by European providers. So far, however, there are far too few providers of such servers in Europe.

This later aspect will presumably change in due time due to the tremendous market demand for cloud based medical data storage, but up to now, it clearly was a major aspect why the development of an "*Internet of Medicine" in* Europe took so long and is still not yet deployed.

As a patient who is treated in a European hospital, one can quickly experience this disadvantage. The data collected during the hospital stay remain in the respective hospital and are usually not digitally accessible from the outside. This means, for example, that the patient's general practitioner has no access to this data and may re-initiate certain diagnostic procedures that would not actually be necessary because the relevant data were already available in the hospital. This circumstance is an important factor also in terms of health care costs and could be significantly improved by a secure and certified cloud solution. The patient would also be spared the side effects that can accompany the diagnostic procedures.

Thus, there is a clear and well justified need for an "*Internet of Medicine"* to be able to keep pace with the exponential technical development in information technology in medicine. The opportunities are huge, but the tasks ahead are also difficult and complex. It will be important to reach a reasonable consensus among all parties involved in order to develop an economically viable and pragmatic approach. Here, Europe, and Germany in particular, with its very thorough approach in data protection, would be particularly well suited to develop solutions that would also find interest and application far beyond Europe's borders.

References

Brönneke, J. B., Debatin, J. F., Hagen, J., Kircher, P., & Matthies, H. (2020). *DiGA VADEMECUM: What to know about digital health applications*. MWV Medizinisch Wissenschaftliche Verlagsgesellschaft. Kindle version.

Heuveline, V., & Stiefel, V. (2021). The history and future of artificial intelligence. In R. M. Holm-Hadulla, J. Funke, & M. Wink (Eds.), *Intelligence*. Heidelberg University Publishing. (in this volume).

Kierkegaard, S. (1923). *Die Tagebücher 1834–1855, selection and transmission by Theodor Haecker*. Brenner-Verlag.

Mesko, B. (2021). *The medical futurist: A guide to artificial intelligence in health care*. Webicina Kft.

Rombach, R., Esser, P., & Ommer, B. (2021). *Making sense of CNNs: Interpreting deep representations & their invariances with INNs*. arXiv:2008.01777v1 [cs.CV]. Retrieved from https://www.semanticscholar.org/paper/Making-Sense-of-CNNs%3A-Interpreting-Deep%26-Their-Rombach-Esser/8157f156ff4a73a2b069b820cd5cfc90fa501c79

Magnus von Knebel Doeberitz is Professor of Molecular Oncology and Medical Director of the Department of Applied Tumor Biology, Institute of Pathology at Heidelberg University. He is also Head of the Clinical Cooperation Unit F210 of the German Cancer Research Center and belongs to the Molecular Medicine Partner Unit of the European Molecular Biology Laboratory (EMBL_MMPU). He was founder and board member of several biotech companies, including mtm-labs (www.mtm-labs.com), which was acquired by Roche in 2011, ViMREX LLC. and PAICON LLC. Magnus von Knebel Doeberitz spent his postdoctoral period in the laboratory of Nobel laureate Harald zur Hausen at DKFZ. In 1995, he was appointed Professor of Molecular Oncology at the Department of Surgery at the University of Heidelberg. In 2001, he became Medical Director of the Department of Applied Tumour Biology at the University of Heidelberg. His main scientific interests are the mechanisms of human carcinogenesis by papillomaviruses and the lack of DNA mismatch repair. He identified novel biomarkers and therapeutic targets and validated them in clinical trials. He has co-authored more than 300 *peer-reviewed* articles. He is an associate editor of the *International Journal of Cancer* and serves on the editorial boards of several other oncology journals. He has received numerous scientific awards and is an inventor on several patent families in his research areas.

Part V
Economic Intelligence

Chapter 17
The Industrialization of Intelligence

Michael Byczkowski and Magdalena Görtz

Abstract In the following chapter, we will show, based on the fundamental concepts of observation, experience, cognition, and skills around the notion of intelligence, in what ways these are interdependent and how modern, especially algorithmic, approaches to Artificial Intelligence are to be classified. We conclude our reflections with an overview of the opportunities and challenges they present, illustrated mainly by examples from the field of medicine.

1 The Pursuit of Cognition

"Dass ich erkenne, was die Welt im Innersten zusammenhält" (That I may understand what binds the world together at its innermost core) (Goethe, 1994) — Since the beginning of time, humanity has been striving for knowledge, mainly using its given intelligence to achieve that goal. The word intelligence is derived from the Latin root *legere,* meaning "to gather", "to assemble", or "to compile". Furthermore, the related word *intellegere* means "to know", "to understand", "to perceive", and "to select". Thus, intelligence refers to the ability to learn and understand, to deal with situations, and to apply cognition and skills to respond to one's surroundings.

In this paper, we want to give a brief overview of the current state in this field of study, in what ways intelligence can be supported and how the findings can be applied on a broad scale. In this context, the so-called Artificial Intelligence (AI) is increasingly playing an important role, which we want to classify in this frame of reference. Although the great advances in this field do not necessarily lead to the recognition of "what binds the world together at its innermost core", one can develop

M. Byczkowski (✉)
SAP SE, Walldorf, Germany
e-mail: michael.byczkowski@sap.com

M. Görtz
Department of Urology, Heidelberg University Hospital, Heidelberg, Germany
e-mail: magdalena.goertz@med.uni-heidelberg.de

R. M. Holm-Hadulla et al. (eds.), *Intelligence - Theories and Applications*,
https://doi.org/10.1007/978-3-031-04198-3_17

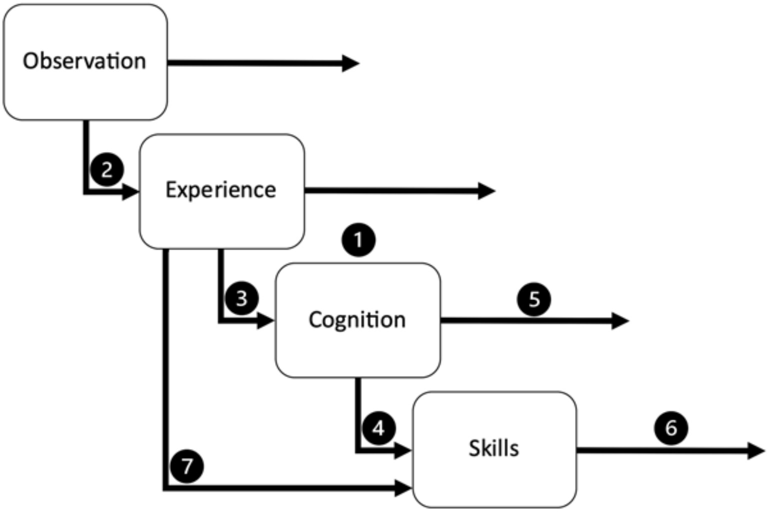

Fig. 17.1 The course of the article in seven steps: (1) The pursuit ofCognitionpursuit of cognition. (2) From observation to experience. (3) From experience to cognition. (4) From cognition to skills. (5) The spread of cognition. (6) The spread of skills. (7): From experience directly to skills. (Source: Own representation)

many useful applications for industrial aspects in addition to the scientific research *itself*. This can be carried out with the help of machine support and by observing the world and gaining experience from it.

Looking at the evolution of progress over the past few centuries, we can distinguish four stages of the industrial revolution. These lead from the use of the first mechanical production facilities over the introduction of production based on the division of labor and the use of information technology (IT) to automate production, to the final and fourth industrial revolution, the complete digitalization and networking of industrial production (Kagermann et al., 2011). Today it is widely assumed that the current fourth industrial revolution (Industry 4.0) is significantly influenced by the use of Artificial Intelligence, if not replaced by a new, fifth industrial revolution in the near future. This article will highlight the developmental stages of intelligence using selected examples from medicine, list possibilities of Artificial Intelligence, and point out challenges in the application of intelligent machines (Fig. 17.1).

2 From Observation to Experience

One can only speculate how many people came to their deaths while tasting unknown plants until enough experience was gathered among the surviving spectators to either avoid certain plants or use special preparation methods: the nutritious root tubers of the cassava plant, for instance, contain significant amounts of hydrocyanic acid, making them poisonous in their raw state. For example, in South America, the tubers are therefore peeled, grated, soaked, and then dried again so that the hydrocyanic acid can escape (Soentgen & Hilbert, 2012).

Similar—though much more focused—experiences were also made in early medical studies: one example of this is the British ship doctor James Lind. Due to the dramatic death toll from scurvy during long sea voyages, he conducted the first controlled comparative study in the history of medicine in 1747, identifying the use of citrus fruits as an effective way of treating scurvy. The existence of vitamins and knowledge of scurvy as a vitamin C deficiency disease were entirely unknown at that time. Lind discovered the effect citrus fruits had on scurvy by dividing scurvy-suffering sailors into different groups who followed different diets. Although the actual causality, vitamin C deficiency, remained hidden, an improvement in the patients' condition was still possible based on the statistical results (Baron, 2009).

3 From Experience to Cognition

In the course of his research in the field of behavior of electron beams in a vacuum, the physicist Wilhelm Conrad Röntgen discovered a previously unknown type of radiation that was both invisible and extremely penetrable. He called these "X-rays" and realized that materials were penetrated by these rays to different degrees depending on their density (Röntgen, 1895). Röntgen understood that X-rays are absorbed to different degrees by tissues of varying density in the human body. He concluded that this could be used to see inside the body, to detect broken bones before a surgery, for example. The realization that the rays could also cause adverse effects in the human body was only obtained later.

4 From Cognition to Skills

The invention of the X-ray tube was a pioneering step toward the widespread practical application of X-rays. A generator was used to produce the high voltage needed to operate the tube. In the X-ray device, electrons were released from a cathode and accelerated by the potential difference in the generated electric field. An anode was located at the other end of the X-ray tube; and the copper atomic nuclei of the anode strongly decelerated the electrons when they struck. This caused the electrons to emit energy in the form of electromagnetic waves, the X-rays. The construction of the X-ray tube made it possible to use X-rays in a targeted manner. Physicians soon found the first practical ways of application: in addition to diagnostic imaging via the use of photographic plates, they also began experimenting with irradiating ill people, especially those suffering from cancer and tuberculosis.

Today, the field of medicine would be unable to do without imaging techniques and this field of study keeps progressing: the most recent discovery in the application of X-rays is X-ray microscopy, which can be used to look inside cells among other forms of application (Yamamoto & Shinohara, 2002).

Another innovative development of X-rays is computed tomography, which can represent objects three-dimensionally by means of tomograms. Transferring the gained knowledge into widespread application has proved to be particularly hard, both in the translation itself and in the commercial use of findings. Large-scale equipment of the latest generation in radiology often exceeds the financial scope of hospitals. We will not go into detail about the challenges that arise during implementation; to interested readers we recommend, e.g., (Gruss, 2012). Furthermore, it is worth mentioning that Röntgen was honored with the Nobel Prize in physics in 1901, but at the same time refrained from patenting his invention in order to enable a quicker application for the benefit of all.

5 The Spread of Cognition

In addition to the learning of skills, the underlying knowledge is highly important in order to be able to logically assess the applicability of the individual skills in the respective situations. Theoretical scientific teaching at universities and university clinics is not the only way of imparting knowledge; scientific contexts must also be made easy to understand in order to make the greatest possible positive contribution to a number of people outside of academic teaching institutions. One example of achieving this is simulation: For instance, the use of virtual reality enables practical, multi-dimensional insights into anatomy through the physical detail it provides. This can be used to supplement pathology courses in medical training and to realistically simulate surgical procedures. A significant goal for the future is to create exact digital twins of patients, which can not only be used to simulate interventions, but also to validate diagnoses and simulate treatment alternatives and their results.

6 The Spread of Skills

Individual skills acquired through years of practice and training are limited to the practitioner alone; this holds true both for skills in special surgical techniques, and efficient examination methods. To have the greatest possible impact on fields like, for example, routine clinical practice, skills must be disseminated, meaning their teaching and performing must be simple. Two practical examples are minimally invasive surgery, including surgical robotics, and telemedicine.

Maximilian Nitze was working on experiments on the possibility of illuminating internal hollow organs. For the technical implementation of his experiments, he received support from an instrument manufacturer. By 1879, he had developed the endoscope, a device which enabled a light source to be guided into the interior of the organ in order to be observed. This achievement demonstrated new diagnostic possibilities (Nitze, 1879).

The use of the rigid endoscope in laparoscopy for inspection of the abdominal cavity was another important innovation. After that, operations could be performed using small incisions through inserted endoscopes, e.g., for appendectomy. During this process, the surgeon operates the instruments and evaluates the surgical procedure via screen. The introduction of minimally invasive surgery to evaluate the abdominal and pelvic organs allows patients to become mobile and pain-free more quickly compared to open incision surgery. Endoscopy was not the end point of this chain of developments, though: the mechanical limitations remained, because the instruments were straight, and required a completely new approach. This new approach started around 100 years later, when the field of surgery was revolutionized by the Da Vinci robotic surgical system developed by Intuitive Surgical. The system's robotic arms can translate hand movements and have three-dimensional views with magnification options that allow surgeons to achieve significantly greater precision. Not only are the possibilities of modern endoscopy integrated, but additional joints in the manipulation arms of the surgical robots also make movements in the smallest of spaces possible. These movements could neither be performed by the human hand in open surgery nor by means of the established rigid endoscopes. However, the robotic surgical system does not operate autonomously; it continues to be operated by the surgeon (United States of America Patent No. US 2020/0368915 A1, 2020). Additionally, training modules for the robotic consoles allow the surgeon to train in the use of the various devices outside of procedures, thereby increasing their own skills.

The other example, telemedicine, follows on almost seamlessly: thanks to modern robotics and fast internet connections (e.g., by means of 5G telecommunication networks), operations can even be performed when the surgeon and patient are not in the same building. This is necessary for operations where the specialist is not spatially available, where high radiation exposure is to be expected in the operating theatre, or where the treatment environment is inaccessible, for example, during research stays in Antarctica or on space flights.

Even beyond the physical manipulation transmission by a robot, telemedicine can disseminate skills: over long distances, second opinions can be given, examinations can be supported, and diagnoses can be made by experts who, for a variety of reasons, cannot be present on site themselves, all via video conferencing.

It must be kept in mind though, that it is of eminent importance to use these new, disseminatable skills ethically and responsibly. For example, the local health care system in a small country can quickly be destroyed by a massive telemedicine offer from a highly scaling (technology) provider, leading to the migration of many local doctors to other countries. This can be highly problematic, since if further samples need to be taken or treatments need to be carried out locally after a successful diagnosis, there is a lack of trained doctors at the actual point of care.

7 From Experience Directly to Skills

Through the progressing automation of all the procedural steps listed above, gigantic amounts of data are now generated and, due to the availability and price attractiveness of storage media, they can be accessed quickly and easily and stored without great costs. While previously only relevant data was selected and archived, it is now easily possible to store all data, at least for a certain time, enabling more evaluations.

The resulting huge amounts of data, often referred to as “data lakes”, can contain data in both structured and unstructured form and are often at first not collected in their entirety for a predetermined purpose or special evaluation. For example in the medical environment, some of the data serves to document the medical procedure performed, e.g., in the form of electronic patient records or image data from a computed tomography machine, to be used in diagnoses or treatments. Other data records describe the activities of a machine itself. Using that data, indications of possible operating errors, impending component failures, or deviations in measurements can be obtained, thus initiating timely intervention by medical personnel or other machines. This data is therefore mainly used for validation of results and quality assurance. However, the majority of the available data is not geared to specific purposes and its immense quantity makes it inaccessible to direct evaluation by humans.

Therefore, this portrays an immediate application area for important subfields of Artificial Intelligence and, in particular, Machine Learning (ML) and Pattern Recognition: such algorithms can sift through these data lakes tirelessly to spy statistical anomalies that humans would not be able to notice. This can be done in two ways: The machine can be given both raw data as input and the corresponding responses, as annotated output, to derive rules on its own. These new rules are then applied to new data to produce answers in the form of predictions. The algorithms improve themselves in the process and “learn” from trial and error, just as humans do from experience. Alternatively, it can also examine the entirety of the unchanged data for statistical anomalies, i.e., patterns in the sense of statistical models; this is also referred to as unsupervised learning, as opposed to the aforementioned supervised learning.

The results that these algorithms deliver are mostly of a purely statistical nature, i.e., probabilities of correlations. This is commonly known from the weather forecast: “in 90% of the cases with the same weather situation it has rained”. The forecast does not say it rains 90% of the time within a time period, nor why this is the case. However, the information is useful to the user when it comes to choosing the right clothes for the day, the underlying causality is not relevant for this. Therefore, based on the available data, a skill of weather or rain prediction was developed from experience, without a meteorologist having made a forecast in a particular case or the user having meteorological knowledge. The result is purely application-oriented and serves to support decision-making by providing a skill without knowledge of the meteorological context.

In this sense, large amounts of medical data can also be evaluated and used in different ways: individuals can compare themselves with relevant data from the data lakes and, for example, receive behavioral recommendations for their individual vital parameters, and at the same time contribute data directly by themselves via fitness trackers and other personal measuring devices. Physicians can thus be alerted to conspicuous correlations in the recorded cohorts and in this way be supported in their decisions in diagnosis and therapy.

8 From Data to Artificial Intelligence

As previously described, it is essential to have high-quality data available for the machine detection of correlations (Roberts et al., 2021). Providing this is not easy though: on the one hand, the data must be obtained in a legally compliant manner, i.e., in particular, the data and patient protection of the respective country must be strictly observed. Additionally, data collection and use, e.g., in medical research, must be safeguarded by appropriate ethics applications. On the other hand, the data must be correct and relevant, meaning it must also represent the typical patients in a sufficiently diverse way. Furthermore, the data should ideally include all those characteristics that could represent a correlation to the expected outcomes. For these reasons, in addition to the demand for free access to data (especially in the case of public sector data, which is after all mostly generated by tax revenue) and data donation, e.g., for research purposes, the view of data as an economic good is gaining ground in practice. Data can have a high inherent value, so it is sensible and appropriate for all those involved in a value chain to have an appropriate share in the overall created value.

The dependence of the trained AI algorithms on the data also leads to new challenges in support and maintenance: here, errors can lie not only in the algorithm itself but also in the data provided for training. This becomes even more of a challenge when it is not just a central and thus well-controlled dataset from a vendor, but customer-specific data lakes that are used by the AI algorithms, for example, the specific data lake of an individual clinic. This data, being collected across many departments and over long periods of time, is often variable in quality and based on different cohorts with varying characteristics; errors in the annotation of data are particularly relevant here. In any case, it must therefore also be possible to determine which data led to which conclusions, in order to enable not only corrections to the programming but also an “un-learning.” This means the targeted forgetting of parts of what was once learned, if it was based on inadequate data. These measures are necessary to meet the strict requirements of individual approval directives such as the EU Medical Devices Directive (Regulation [EU] 2017/745 of the European Parliament and of the Council of 5 April 2017 concerning medical devices, 2017) and also to be able to demonstrate the effectiveness of an AI-based algorithm. This requires the selection of a fixed and preferably representative data set that is used to train the AI module, which is then tested and certified accordingly. The module certified in this way is then used as the finished product. However, it cannot learn directly from the respective cases that were treated with it, since otherwise the certification would no longer apply due to a changed database and an independently traceable validation would not be possible. Instead, data is collected separately and only used for the optimization of a future product version, which then undergoes the same rigid certification process based on the updated data set. Not only does this help meet the regulatory requirements described above, it also facilitates maintenance. The price to be paid, however, is that the respective version of such a program does not continue to learn with each currently treated patient, but always retains the same level of "smartness" during the entire period of use of a program version; only a later version can supply new insights, if necessary.

It is also interesting to compare AI algorithms with each other by training different algorithms with the same data to explore differences in efficiency and effectiveness of the underlying algorithms neutrally, so to speak under laboratory conditions. For example, the CheXpert dataset from the Stanford Machine Learning Group deserves special mention here. It contains over 220,000 recordings from over 65,000 patients (Irvin et al., 2019) and even showcases a ranking of algorithms (Rajpurkar, 2017).

It is also essential in this context that health-related data require particular protection and that companies often have proprietary interests in the data they collect and sometimes also process at great expense. One possible solution to this is federated learning, a technique in the field of Machine Learning in which a model can be trained on multiple devices simultaneously. Each institution can thus train with its own local dataset that is not shared with other participants (Kaissis et al., 2020). Another very interesting technology in this context is *Secure Multiparty Computation*, where computations are performed on different datasets that cannot or should not be pooled at a single individual for confidentiality reasons; think, for example, of studies that are to be performed across institutions or even transnationally, but the respective data should remain at the respective organizations (Frikken, 2010).

Often, however, individuals also want to use these new possibilities of AI-based algorithms for themselves: this is where health trackers such as Fitbit or Apple Watch come in handy. These can monitor heart rate, activity levels, and also sleep; individual device types are even not inferior to professional electrocardiograms (ECG) in many aspects (Ott, 2018). These new achievements can warn the user of deviations, give the physician a better idea of the patient's condition over a longer period of time, and autonomously suggest preliminary analyses.

9 From Correlations to Causations

In the end, the examples mentioned above are pure correlations, i.e., statistical abnormalities and indications; they are not directly accompanied by an insight into causal dependencies. However, Artificial Intelligence can also help here: it can support researchers in finding those interesting areas of "data lakes" which, supported by further investigations and clinical studies, can be promising areas for new, this time causal, findings.

Furthermore, expert systems, which are a special form of Artificial Intelligence, can be created on the basis of formalized specialist knowledge and are capable of drawing new conclusions by logically linking this specialist knowledge. Particularly noteworthy in this respect is the medical expert system MYCIN (Shortliffe, 1976), which was started at Stanford University as early as 1972 and is intended to support the physician in the diagnosis and therapy of infectious diseases. It was further developed in its ONCOCIN form for use in cancer treatment (Shortliffe et al., 1981). A major advantage of such expert systems is that the conclusions derived can always be logically traced back and it is clear at all times how the system reached a certain result.

The goal continues to be the explanation of the system at hand through explicit formation of new models, completely independent of statistics, underlying data, and environmental observations so that in the end, even the previously chosen shortcut from experience to skill offers a path to insight and pure knowledge based on causation can be gained. Here, the so-called field of "Explainable AI" (XAI (Turek, 2016)) is particularly interesting. The goal is to provide explanations for the results to the "black box" that Machine Learning often conveys so that more confidence can be placed in those results. This is particularly important in broad applications and socially relevant cases, such as credit score attribution. For example, the "right to explanation" is explicitly enshrined in Recital 71 of the EU General Data Protection Regulation (Regulation (EU) 2016/679 of the European Parliament and of the Council, 2016).

10 Models as Representations of Reality

Basically speaking, the training of Artificial Intelligence algorithms is another way of creating models; in this case, the automatic creation of stochastic models in a broader sense. This raises the same question as for all models that are representations of reality: in which areas does the model provide a sufficient description of reality, and where are the limits of reliable model application?

This is all the more important when it comes to models in medical diagnostic support and therapy: who would want to be treated in a way that has not been successfully tested on a corresponding part of the population in a clinical trial? Many statements cannot be easily transferred from one cohort to another, even if adjacent: just think of the medication of adults versus children or pregnant women.

Therefore, for a successful application of AI in broad medical practice, it is indispensable that the treating physician is also able to comprehend the diagnosis or treatment suggestion generated by the AI in detail, especially from a professional and not only from an informatic/technical point of view. Above all, it is important that it becomes comprehensible on the basis of which correlations a recommendation was made, because it is quite possible that special characteristics of a patient were not represented at all in the training data of the related cohort. One example to illustrate this is the clinical condition of dextrocardia, in which the heart is located on the right side of the body; a pain in the right half of the body is therefore to be interpreted quite differently than in the general population.

Medical-technological progress must also be regularly and explicitly included in the modeling of Artificial Intelligence: if, for example, the training cohort does not use a new drug or another new form of therapy, the algorithm cannot make any suggestions in this regard because it has not yet been trained with this data and thus has no knowledge about it.

However, the possibilities of assessment by the physician are very quickly limited, especially if the AI algorithm analyses large amounts of data across disciplines and takes numerous different characteristics into account. The depths of analysis reached can then no longer be adequately assessed even by teams of doctors across disciplines. In this case, it is precisely the speed and scope of data processing that is a strength of the machine; a return to the general scholar or polymath is therefore not a valid option, because new knowledge is generated so quickly every day that humans can no longer keep up.

The legal and liability issues associated with the use of algorithm-based decisions are only touched upon here and are in principle similar to those currently being discussed with regard to autonomous driving (Gasser, 2015).

So, will we end up needing redundant systems that support the user, in this case the treating physician, in the best possible way to optimally diagnose and treat the patient, while also effectively controlling themselves, for example by using different algorithms or comparison data sets to validate results and recommendations? It is likely that this assumption is true, at least in those areas where the underlying causations have not yet been sufficiently derived.

11 Outlook

Artificial Intelligence algorithms will be an even more integral part of our lives in the future. Therefore, it is important to educate the next generations on the concepts and applicability of Artificial Intelligence and show them how they can work efficiently in a workspace together with machines to achieve higher precision and productivity. In this context, machines are not to be understood as competitors or opponents to humans, but the goal is to create an interaction between humans and machines in order to enrich and augment the capabilities of humans in mechanical, cognitive, and intellectual terms.

However, one can be certain of one thing: the doctors themselves, with their combined knowledge and intuition, cannot be replaced by an (AI) algorithm, at most by other doctors who are additionally skilled in the intelligent use of AI algorithms.

References

Baron, J. H. (2009, June 1). Sailors' scurvy before and after James Lind — A reassessment. *Nutrition Reviews, 67*(6), 315–332. Retrieved from https://academic.oup.com/nutritionreviews/article/67/6/315/1807435

Frikken, K. B. (2010). Secure multiparty computation. In *Algorithms and theory of computation handbook: Special topics and techniques* (pp. 14-1–14-16).

Gasser, T. M. (2015). Grundlegende und spezielle Rechtsfragen für autonome Fahrzeuge. In M. Maurer, J. C. Gerdes, B. Lenz, & H. Winner (Eds.), *Autonomes Fahren* (pp. 543–574). Springer Vieweg. https://doi.org/10.1007/978-3-662-45854-9_25.pdf

Goethe, J. W. (1994). In A. Schöne (Ed.), *Faust. Eine Tragödie*. Deutscher Klassiker Verlag.

Gruss, P. (2012, August 29). Von der Erkenntnis zum Gewinn. *Rotary Magazin für Deutschland und Österreich*. Retrieved from https://rotary.de/wissenschaft/von-der-erkenntnis-zum-gewinn-a-1579.html

Irvin, J., Rajpurkar, P., et al. (2019, January 21). *CheXpert: A large chest radiograph dataset with uncertainty labels and expert comparison*. AAAI. Retrieved from https://arxiv.org/abs/1901.07031

Itkowitz, B. D., DiMaio, S. P., Halabe, D. J., Hasser, C. J., Hoffman, B. D., Larkin, D. Q., Zhao, W., et al. (2020). United States of America patent no. US 2020/0368915 A1.

Kagermann, H., Lukas, W.-D., & Wahlster, W. (2011). Industrie 4.0: Mit dem Internet der Dinge auf dem Weg zur 4. industriellen Revolution. *VDI Nachrichten*(13), S. Industrie 4.0: Mit dem Internet der Dinge auf dem Weg zur 4. industriellen Revolution. Retrieved from https://www.dfki.de/fileadmin/user_upload/DFKI/Medien/News_Media/Presse/Presse-Highlights/vdinach2011a13-ind4.0-Internet-Dinge.pdf

Kaissis, G. A., Makowski, M. R., Rückert, D., & Braren, R. F. (2020, June). Secure, privacy-preserving and federated machine learning in medical imaging. *Nature Machine Intelligence 2*, 305–311. Retrieved from https://www.nature.com/articles/s42256-020-0186-1

Nitze, M. (1879, June 14). Eine neue Beobachtungs- und Untersuchungsmethode für Harnröhre, Harnblase und Rectum. In *Wiener Medizinische Wochenschrift* (pp. 649–652). Retrieved from https://anno.onb.ac.at/cgi-content/anno-plus?apm=0&aid=wmw&datum=18790003&seite=00000325

Ott, P. (2018, September 30). *Podcast MST007 — Latest: Apple watch*. Retrieved from Medical Standard Time: https://medical-standard-time.com/358/mst007-aktuelles-apple-watch/

Rajpurkar, P. (2017). *CheXpert: A large chest x-ray dataset and competition*. Retrieved from Stanford ML Group: https://stanfordmlgroup.github.io/competitions/chexpert/.

Regulation (EU) 2016/679 of the European Parliament and of the Council. (2016, April 27). Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32016R0679

Regulation (EU) 2017/745 of the European Parliament and of the Council of 5 April 2017 on Medical Devices. (2017, April 5). Retrieved from https://eur-lex.europa.eu/eli/reg/2017/745/oj?locale=en

Roberts, M., Driggs, D., Thorpe, M., et al. (2021, March 15). Common pitfalls and recommendations for using machine learning to detect and prognosticate for COVID-19 using chest radiographs and CT scans. *Nature Machine Intelligence 3*, 199–217. Retrieved from https://www.nature.com/articles/s42256-021-00307-0

Röntgen, W. C. (1895). *Ueber eine neue Art von Strahlen (Vorläufige Mittheilung)* (2nd ed.). Stahel. Retrieved from https://www.deutschestextarchiv.de/book/view/roentgen_strahlen_1896

Shortliffe, E. H. (1976). *MYCIN, computer-based medical consultations*. Elsevier.

Shortliffe, E. H., Scott, A. C., Bischoff, M. B., Campbell, A. B., Melle, W. V., & Jacobs, C. D. (1981). ONCOCIN: An expert system for oncology protocol management. In P. J. Hayes (Ed.), *Proceedings of the 7th International Joint Conference on Artificial Intelligence, IJCAI '81* (pp. 876–881).

Soentgen, J., & Hilbert, K. (2012, October 2). Präkolumbianische Chemie – Entdeckungen der indigenen Völker Südamerikas. *Chemie in unserer Zeit, 46*(5), 322–334.

Turek, D. M. (2016). *Defense advanced research projects*. Retrieved from Explainable Artificial Intelligence (XAI): https://www.darpa.mil/program/explainable-artificial-intelligence

Yamamoto, Y., & Shinohara, K. (2002, December 26). Application of X-ray microscopy in analysis of living hydrated cells. *The Anatomical Record, 269*(5), 217–223. https://doi.org/10.1002/ar.10166

Michael Byczkowski is Global Vice President and Head of Healthcare Industry at SAP. He studied mathematics at the Ruhr University in Bochum and has worked in Germany and abroad in a wide variety of areas in industrial companies, such as process optimization, project management, and management of global technology partnerships as well as design and innovation areas. A special focus of his work are strategic innovation projects alongside customers and partner companies in global healthcare, currently mainly in the areas of business platform, enterprise networks, data management and exploitation, and AI.

Magdalena Görtz is Senior Physician at the Department of Urology at Heidelberg University Hospital and Head of the Junior Research Group "Multiparametric Methods for the Early Detection of Prostate Cancer" at the German Cancer Research Center. She studied medicine at the Ruprecht-Karls-University in Heidelberg and at Columbia University in New York. Her doctoral thesis on the progression and spread of malignant tumor cells was awarded the Wilma Moser Prize by the Ruprecht-Karls-University of Heidelberg. Her research focuses on developing more individualized approaches for the diagnosis, risk stratification, and therapy planning of prostate carcinoma through integrative data and biomarker analysis. Furthermore, Dr. Görtz is project lead in translational collaboration projects between clinic, research institutions, and industrial companies in the field of AI.

Chapter 18
Intelligent Strategies: Correct Recognition and Good Choices in a Complex World

Dietrich Firnhaber

The universal has given way to the contextual, the local, and the pursuit of the one, single, absolute truth is displaced by a humble respect for the plurality of truths that partially and pragmatically map our world.

(Sandra Mitchell, 2008) (Sandra Mitchell, Complexities. Why we are only beginning to understand the world, p. 152. Suhrkamp 2008, Frankfurt a.M.)

Abstract We live in a world in which our actions and planning are increasingly influenced by manifold linkages and feedbacks. We can neither fully grasp the interrelationships relevant to our goals and initial situation nor evaluate them without error. In short: our world is complex. Long-term planning is not characterized by rigid conditions, but by uncertainties. However, through careful analysis, *known uncertainties* can be named to a certain extent and mapped into scenarios. In this way, strategies emerge whose conditions and prerequisites can and must be simultaneously and permanently considered during the implementation and further planning process. In this way, the planning process and the planning result are given a new stability. Although the new stability does not eliminate the uncertainties, it does lead to a productive management of them. Finally, productive management of the uncertainties requires *open implementation*. Open implementation works out the details of strategy implementation and exposes the conditions and prerequisites of a strategy to a reality check. This feedback loop, firmly built into the planning process, requires the ability to engage in robust dialogue and thus a corresponding open corporate culture.

D. Firnhaber (✉)
Strategy & Portfolio Development, Covestro AG, Leverkusen, Germany
e-mail: dietrich.firnhaber@covestro.com; https://www.covestro.com

R. M. Holm-Hadulla et al. (eds.), *Intelligence - Theories and Applications*,
https://doi.org/10.1007/978-3-031-04198-3_18

1 Introduction

1.1 Problem Definition

Similar to how Kierkegaard looks at life, it is advisable to look at corporate strategies. According to the Danish philosopher, life can only be understood backwards, but must be lived forwards.[1] It is not uncommon for coincidences in life to determine our path, whether fateful or merely insignificant, small events. Which of these events develop into life-directing ones and what impact they have, we usually only grasp in retrospect. We can plan. We can deliberately decide on something, such as a path of education, a place to live and a life partner, even the attitude with which we look at life—we can be aware of all this as influencing our life and decide and yet our life cannot be predetermined in detail and steered precisely to desired results.

Why is that so? We are placed in a context that we can neither fully nor comprehensively comprehend due to its multiplicity and its ever newly arising connections. Much less are we able to map the infinite possibilities of connections in a plan, or even to calculate how unexpected events or rare combinations of events—so-called 'black swans'[2] —will affect us. This applies to our own lives as well as to the 'life' of a company.

In short, it is impossible to say with certainty at the start of a life or business strategy whether it will achieve its goal. The reason is obvious in view of what has been said above: strategies are plans that are oriented towards a future reality with objectives, the realization of which, however, is significantly characterized by uncertainties. Our knowledge of what will affect the shaping of the future is minimal and insufficient, despite continuously increasing knowledge. It is as banal as it is relevant: the future is not predictable.[3] It cannot be developed monocausally or linearly from today. Life plans—corporate strategies are nothing else—cannot therefore follow fixed rules like train timetables; they must take into account the uncertainties of life resulting from complexity.[4][5]

---

[1] 'It is quite true what philosophy says, that life must be understood backwards. But over this one forgets the other sentence, that life must be lived forwards.' Søren Kierkegaard, *Die Tagebücher 1834–1855,* selection and translation by Theodor Haecker, Innsbruck, Brenner-Verlag 1923.

[2] Nassim Taleb, looking at the unexpected events, or rather unanticipated events, has developed the theory of the 'black swan' event. Nassim Nicholas Taleb, *The Black Swan—The Power of Highly Improbable Events*, Albrecht Knaus Verlag, Munich 2007.

[3] With regard to John Maynard Keynes' famous statement 'in the long run we are all dead' probably with one exception. See the full quote about economists' helpful statements about the future: 'In the long run we are all dead. Economists set themselves too easy, too useless a task if, in tempestuous seasons, they can only tell us that when the storm is long past the ocean is flat again.' Ders: *Tract on Monetary Reform*, McMillan & Co, p. 80, London 1923.

[4] On the concept of complexity, see *Historisches Wörterbuch der Philosophie*, Vol. 4: I-K, pp. 939f., eds, Joachim Ritter, Karlfried Gründer, Wissenschaftliche Buchgesellschaft, Darmstadt 1976.

[5] For a very clear study of the challenges of making correct, i.e. goal-oriented, decisions in a complex world, see also Dietrich Dörner, *Logik des Misslingens—Strategisches Denken in komplexen*

1.2 Why Strategic Planning Makes Sense

So why think and plan strategically when even the very best strategy cannot guarantee success? Firstly, because resources (capital, labour, know-how and time) are generally limited, and we should therefore use them in the best possible way.[6] The second reason to be mentioned is the actual subject of this essay. It is both a reason and a challenge for strategy development, namely the unpredictable complexity of our world and the associated uncertainties regarding future developments. We must face this complexity and can perhaps even use it productively to achieve our goals.

Companies—especially when they operate internationally—are exposed to numerous influences that interact in a variety of ways and have reinforcing, overlapping, or even weakening effects. Companies cannot influence most of these effects or can only influence them insufficiently. Their occurrence and effect are fraught with uncertainty. In this context, it is the task of strategy development to *determine the relevant framework*, to *work out the essential effect structures* and to *identify measures to* achieve the objectives. The more complex a structure is, the more agile a strategy must be structured without losing sight of the essential drivers. Without a strategy, a company is left rudderless to the interplay of chance—the uncertainties. Only reaction and not action is possible. With a strategy that incorporates the corresponding requirements, a company will be able to react in a planned manner—secured by a structured and systematic view on the remaining uncertainties—and thus steer through these uncertainties towards the set goal. Thus, the effort is worthwhile, because with Sandra Mitchell, it can be said that uncertain knowledge is still better than ignorance.[7]Modern strategies look at a future several years away. Their applications are bets on the future. Time horizons can be quite different here. In any case, however, they go beyond planned short-term action, i.e. beyond what we call tactics in our parlance.[8] Strategies are thus attempts to achieve certain goals through the best possible use of scarce resources, cast in action plans. The implementation of these action plans is based on decisions that are based on a combination of reliable knowledge and the interpretation of uncertainties.

Even if little can be said about the actual success of a strategy at its starting point, statements can certainly be made about whether a strategy has been well thought out, i.e. well deduced and well set up for implementation. A meaningful statement can be made about this. In short, even if, as a bon mot says, 'planning replaces chance with error', it makes sense to concern oneself with strategy development. It

Situationen, Rowohlt, Reinbek 1989.

[6] However, this is only relevant if we do this in order to achieve a certain goal. If there is no goal, then there is no need for a strategy. If the goal is not set appropriately, the strategy works itself off on the unsuitable object. The latter often results from a lack of or insufficient engagement with the starting point.

[7] Sandra Mitchell, ibid., p. 130.

[8] See for an explanation of the history of concepts under the keyword 'strategy' in *Historisches Wörterbuch der Philosophie*, Vol.: 10 St-T, WBG, Darmstadt, 1998.

is a craft for success, but not a guarantee, because life, to paraphrase Kant, is made of too crooked a piece of wood for that.

There are numerous—and varying—approaches to strategy development.[9] This paper aims to address the question of intelligent strategy in the context of complexity. By its nature, this can only be done on the surface. The *correct recognition of the essential factors* (a), *the good selection of the most suitable options* (b) as well as the *open implementation* (c) will be touched upon here as an attempt to productively face the uncertainty that emerges through complexity.[10]

2 Recognizing and Using the Essential Factors in a Complex World

2.1 Identifying the Key Factors

Strategies therefore provide a frame of reference within which actions are planned in detail in order to achieve a given goal. Let us now look at what will presumably be relevant in the 2020 decade. We are hereby assuming an internationally operating company. The following list can only be a selection of the probable factors[11]:

---

[9] Springer-verlag shows a query of the term Strategy under the heading 'Management+Leadership' on November 28, 2020 at 3:52 p.m. 1121 books at: https://www.springerprofessional.de/search?q.filters[0].values[0]=SPRBook&q.filters[1].mode=0&q.searchType=HeroBookSearch&q.courseType=&q.filters[0].mode=0&q.filters[1].values[0]=Management+%2B+F%C3%BChrung&q.sortType=Relevance&q.page=0&q.query=Strategy&q.filters[1].name=disciplinetaxonomyFacets&q.originQuery=&q.displayQuery=&q.manualSort=false&q.facets=true&q.filters[0].name=documenttype.

The term "strategy development" returned over 895,000 search results in 0.34 s on November 28, 2020 at 4:28 p.m.: https://www.google.com/search?ei=mGvCX9r5FpODhbIPwrul6AQ&q=strategy.development&oq=strategy.development&gs_lcp=CgZwc3ktYWIQAzIECAAQRzIECAAQRzIECAAQRzIECAAQRzIECAAQRzIECAAQRzIE-CAAQR1AAWABg_5MLaABwAngAgAEAiAEAkgEAmAEAqgEHZ3dzLXdpesgBCMABAQ&sclient=psy-ab&ved=0ahUKEwjapZfyxaXtAhWTQUEAHcJdCU0Q4dUDCA0&uact=5One of the most rewarding books on the topic of strategy development is by Gary Hamel and C.K. Prahalad, *Competing for the Future,* Harvard Business School Press, Boston, 1994. See also Ulrich Pidun, *Corporate Strategy - Theory and Practice,* Springer Gabler, Wiesbaden 2019.

[10] A comprehensive account of dealing with uncertainty in the context of strategic planning can be found in Kai-Ingo Voigt, *Strategische Planung und Unsicherheit,* Gabler, Wiesbaden 1992. See further *Daniel Kahneman, Thinking, fast and slow*, Farrar, Straus and Giroux, New York, 2011.

[11] The above list cannot be considered complete or relevant in the same way for all companies. Anyone who wants to get a picture for themselves will quickly find what they are looking for on the Internet. Entering the search term 'global trends 2020' into the Google search engine on December 1, 2020 at 16:41 resulted in 49,700 search results within approx. 0.56 s: https://www.google.com/search?q=%22global+trends+2020%22&sxsrf=ALeKk01fa4yUazypn2Lu2_w42vYc8Z9Alg%3A1617807595955&ei=68htYJDWOaOSlwTVxZOIBw&oq=%22global+trends+2020%22&gs_lcp=Cgdnd3Mtd2l6EAMyBwgAEEcQsAMyBwgAEEcQsAMyBwgAEEcQsAMyBw-gAEEcQsAMyBwgAEEcQsAMyBwgAEEcQsAMyBwgAEEcQsAMyBwgAEEcQsANQAFgA

climate change, China on the rise (not only as a sales market, but also geopolitically and technologically), changing globalization towards regionalization, the increase in local military conflicts, population growth, growing and aging middle class, digitalization of all areas of life, and the risk of pandemics. Finally, the regulatory framework for companies is increasing worldwide. For example, desired behaviour is to be[12] evoked via incentives (such as CO_2 certificates)[13] as well as bonus-malus systems (e.g. social points system in China).

But that is not all. In addition to the influences only touched upon above, companies and their leaders must increasingly face social demands. This is probably the factor with the greatest momentum for change at present. Here it is important to understand that companies in capitalist societies are increasingly seen as responsible players in society.[14] They are ascribed not only a social responsibility, but a responsibility for society as such.[15]

Milton Friedman is often quoted as saying that the only social responsibility of business is to maximize profits.[16] However, complying with laws, paying taxes and creating jobs has not been enough for some time.[17] Many companies have recognized this and have identified a specific 'purpose' for themselves[18], i.e. a purpose that goes beyond simply doing business. In fact, the wind direction has changed here, not only regarding the generation of so-called Millennials, i.e. the generation of employees who pay particular attention to anchoring their activities in a deeper purpose, but also with regard to investors. What was until recently a side note,

YP9TaAFwAngAgAFZiAFZkgEBMZgBAKoBB2d3cy13aXrIAQjAAQE&sclient=gwswiz&ved=0ahUKEwjQ98j4suzvAhUjyYUKHdXiBHEQ4dUDCAw&uact=5.

[12] https://www.zeit.de/wirtschaft/2019-08/ueberwachung-china-sozialkreditsystem-eu-handelskammern, 28 August 2019, 8:59 a.m. Source: TIME ONLINE, dpa, jci.

[13] See Federal Ministry for the Environment, Nature Conservation and Nuclear Safety announcement of 9 July 2020: https://www.bmu.de/themen/klima-energie/klimaschutz/emissionshandel/#c8 381.

[14] It is not possible to address the question of the extent to which China's state capitalist system already systemically contains a corresponding utilitarian component as a demand on the companies operating there.

[15] The referendum in Switzerland on 29 November 2020 on the initiative 'For responsible companies—to protect people and the environment' is an impressive example of an attempt to intervene very fundamentally in corporate freedoms, or to bind them to the basic concept of society. (See FAZ of 28 November 2020: 'The question of responsibility' by Johannes Ritter). The same applies to the supply chain law under discussion in Germany.

[16] Comments on this: Nilsson, Andreas and Robinson, David T., *What is the Business of Business?* (June 13, 2017). *Innovation Policy and the Economy*, Volume 18, edited by Josh Lerner and Scott Stern, Duke I&E Research Paper No. 2017–12, Available at SSRN: https://ssrn.com/abstract=2985301, or https://doi.org/10.2139/ssrn.2985301.

[17] It can be argued that this is a very Anglo-American view and that the idea of overall social entrepreneurial responsibility has already found an equivalent in the Western world since the founding of the Federal Republic with the social market economy. Some insight into the current discussion is provided by Ulrich Döring, *Gewinn - ein Spaltpilz der BWL,* F.A.Z. 30 November 2020.

[18] See https://www.spiegel.de/karriere/purpose-in-unternehmen-die-sinn-frage-a-a9fa36.29-fd8c-4c3e-a553-bf0b23c7ecdf—DER SPIEGEL of 12.07.2020.

namely the idea of investors looking at so-called ESG aspects[19] in their investment decisions, has abruptly become a major factor, indeed a market.[20] The most recent example is the climate change pushing behaviour of the world's largest US asset manager, Blackrock.[21] They took stakes in companies worth a total of $7.43 trillion in 2019, giving them a stake in nearly every major publicly traded company in the world. Blackrock and other investors are pushing companies to become more sustainable. To do so, they use their position as investors through a direct and public approach but also through voting behaviour at shareholder meetings. Regardless of whether so-called higher motives are at work here, investors like Blackrock assume that companies that behave in an ESG-compliant manner will be more successful in the long term and will endure in the long run. The recent global crisis—triggered by the COVID-19 pandemic—presents itself as a social and economic crisis. It is proving these investors right and boosting the corresponding investment behaviour. It has given new, real relevance to the decades-old idea of stakeholder capitalism.[22]

Another emerging topic in the context of sustainability is the circular economy.[23] In the long term, companies will have to adjust to the fact that they will not only have to operate in a climate-neutral manner, but will also have to manage without fossil raw materials as a raw material in the value chain (chemicals) or as a source of energy. In particular, for companies that require large-scale plants for their business, i.e. that are generally looking for investment security extending over one or more decades, these emerging changes are of existential importance and must already be taken into account in their strategies today.

It is precisely the emerging simultaneity of social pressure in Western countries towards greater sustainability in entrepreneurial activity and the corresponding impact on investor behaviour that could create a corresponding space for investment in new technologies. Innovative companies, investors willing to take risks and stable

[19] ESG stands for 'Environment, Social, Governance' and expresses the impact a company has on the environment, society and on good corporate governance itself in terms of its behaviour and products. See also the publications of the World Economic Forum, which plays an essential role here: https://www.weforum.org/agenda/2020/01/stakeholder-capitalism-principle-practice-better-business/ and https://www.weforum.org/agenda/2019/12/davos-manifesto-2020-the-universal-purpose-of-a-company-in-the-fourthindustrial-revolution/.

[20] See FAZ of 07.05.2019 https://www.faz.net/aktuell/finanzen/finanzmarkt/nachhaltiges-investing-the-financial-markets-as-world-savers-16173627.html.

[21] Handelsblatt, July 14, 2020, "*Blackrock cracks down on climate protection*" https://www.handelsblatt.com/finance/bank-insurance/esg-criteria-blackrock-grabs-down-on-climate-protection/26000222.html?ticket=ST-2530765-DEb1o2udbBXFCUiRPveL-ap4.

[22] See in place of many and with further references: Dug Sundheim, Kate Starr, *Making Stakeholder Capitalism a Reality*, HBR January 20, 2020 https://hbr.org/2020/01/making-stakeholder-capitalism-a-reality, and Klaus Schwab, *Stakeholder Capitalism*, John Wiley & Sons, Hoboken 2021.

[23] The term 'circular economy' is seen as an alternative to today's predominantly linear economy, in which the waste that is no longer recycled is at the end of the value chain. Further information: https://de.wikipedia.org/wiki/Kreislaufwirtschaft retrieved on 20.01.2021 at 13:32.

governmental framework conditions are the prerequisites for successfully shaping change.[24]

As already mentioned, the topics addressed above only throw an incomplete spotlight on the aspects that must be taken into account in environment analysis. The techniques and approaches of environment analysis are just as diverse as the topics.[25] Their use depends on the actual problem. As a rule, a combination of the various considerations will be appropriate to work out the determining factors. A magic-formula is not available here. As is so often the case, it is advisable to cast the net wide at first in order to then narrow down the criteria with a view towards what is to be achieved.[26]

2.2 The Use of Key Factors in Scenarios

Detached from the question of *how* and *which* trends and tendencies are relevant to the company in question, it is crucial to recognize that these issues are interwoven in many ways; they form an almost impenetrable web of cause and effect and backlash. It is now a truism that our thoughts and actions take place in a complex world. In other words, in a world in which linear and particularistic thinking is not sufficient to make sense of reality and the possible development of the future. A world that, despite growing knowledge, we do not understand so completely that we can eliminate the uncertainties in respect of a goal lying in the future. At best, we are able to build models that represent isolated partial aspects. However, the comprehensive supra-model will not exist, because there is neither complete knowledge of the individual aspects, nor sufficient knowledge of how these aspects interact, nor sufficient computational capacity to capture the infinite possibility of combinations on a longer timeline. The inherent uncertainty contained in a determination of the future cannot be eliminated. If everything is linked to (almost) everything, then it is important to determine the paths that have the highest relevance for the respective strategy development. In other words, the factors that, after careful analysis of the environment, are presumed to have the greatest consistency and thus significance for the achievement of the goal must be placed in relation to one another.

---

[24] In this brief consideration, it is not possible to go into the corresponding goals of the Chinese government's 14th Five-Year Plan.

[25] *The* best known are the PEST or PESTEL analysis, which refers to various environmental factors, see: https://en.wikipedia.org/wiki/PEST_analysis, and Porter's 5-forces: Michael E. Porter: *Competitive Strategy: Techniques for analyzing industries and competitors: with a new introduction*. Free Press, New York 1980.

[26] For strategy development, it is true that narrowly defined analyses provide a good and sharp insight, but a long-term stable decision-making situation is only possible through multiple perspectives.

This is where strategic planning uses the instrument of scenario planning.[27] Scenarios are—if you will—theories about the future. They are based on hypotheses and are thus epistemologically on the same shaky ground as any scientific thinking and political action.[28] Scenarios are therefore fallible theories about the development of the future and not a determination of the future with the '*ex cathedra*' effect of the CEO or the strategy department.

The scenario technique can therefore only help to map possible developments from the combination of selected factors, without underpinning these with a reliable probability of occurrence, i.e. minimising the uncertainty in planning. Sandra Mitchell points out that 'in complex systems, uncertainty is extensive, multifaceted, and often nonlinear'.[29] The technique of scenario planning thus helps to identify potential and plausible developments and the effect of relevant factors, but nothing more. Too often, however, it is used to create the most positive and appropriate picture of the future.[30] Scenario insights are not only relevant in the development of strategies. It takes on a special and often unused significance in the analysis of success as part of the continuous review of the strategy in the implementation phase. More on this below.

3 Selection of Suitable Options

3.1 Understanding the Initial Situation and Identifying the Business Model

Even if the selection of the essential factors and their linkage to relevant scenarios has been successful, a decisive aspect is still missing for the effective establishment of a strategy: this is the in-depth analysis of the starting situation. This is not about the analysis of the environment, but about the analysis of oneself. Even if some of the common ways of looking at things here bring both questions into overlap, the

[27] For general information on scenario technology, see: https://de.wikipedia.org/wiki/Szenariotechnik retrieved on 20/03/2021 at 14:07. For more in-depth information, and in particular on the possibilities of computer-supported 'robust adaptive planning' (RAP) see Robert J. Lempert, Steven W. Popper, Steven J. Bankes, *Confronting Surprise,* in Social Sience Computer Review, pp. 420 ff., 2002.

[28] Fundamental to this: Karl R. Popper in *Logik der Forschung*, eighth edition, J.C.B. Mohr (Paul Siebeck), Tübingen 1984.

[29] Sandra Mitchell, ibid., p. 113.

[30] The history books are full of examples of state leaders and corporations who have allowed their desire and view of the past to guide them into the future, rather than a clear analysis of the changes that are on the horizon. On the thinking traps in decision making: Highly recommended Daniel Kahneman, *Fast Thinking—Slow Thinking,* Siedler Verlag, Munich 2012.

focus on the starting point is crucial.[31] In its importance and degree of difficulty, self-analysis is too often underestimated. An incomplete or even incorrect analysis of the initial situation is fatal and puts a strategy in a hardly correctable misalignment right from the start.

The analysis begins with the identification of the distinct businesses that are in a company's portfolio. In the case of a manufacturer of machines, for example, this can be the development and production of the machines themselves, the sale of spare parts, the maintenance of machines, and also digital services (linking utilization and performance data with market sales data from the customer). These four activities are in fact four very different businesses that follow very specific rules and that generate revenues and profits in very different ways and with very different core competencies.[32]

Different businesses correspond to specific business models developed by theory and practice. A business model describes what services are used to earn money and how.[33] A well-sorted view of a company's business model(s) helps to determine what are relevant activities and capabilities, i.e. which *core capabilities* must be present, and which may be lacking in order to be successful. Looking at the core activities and capabilities of a business model helps not only to understand what is relevant but also to determine what specific and, at best, proprietary advantages a company may have in its individual businesses, or whether any such advantage exists in the combination of the individual businesses. Although this element of self-reflection is immensely important, it shall not concern us further here. The reference to its relevance should suffice at this point.

3.2 Selection of Options as a Creative Process

The selection of options is the actual creative aspect of strategy development. Here, decisions must be made on which path to take based on robust scenarios and an assessment of the specific competitive advantage. Strategies do not appear out of nowhere and are rarely brilliant ideas of one individual, but the result of good analyses and even more of robust discussions in which the participants are equally able to face the realities (initial situation) as well as the uncertainties. Here, solid analysis must meet visionary leadership trained on reality. The scenarios formed by selecting the essential factors shape the framework of the top management's discussion. The

[31] Surprisingly often too little attention is paid to the initial situation. According to the author's experience, this is the basis for serious planning errors. The actual position in the market, skills and abilities are often overestimated or others overlooked. Wishful thinking on the part of the management as well as the often assumed expectations of investors often play a role in the decision for a strategy.

[32] It is not necessary to go into detail here about the fact that even the separation of this activity into separate business units can be a sensible strategy.

[33] See for a good overview: https://en.wikipedia.org/wiki/Business_model Retrieved on

more disruptive a scenario is, the more comprehensive the discussion of possible paths must be. Sprints[34] with participants from the most diverse areas of a company are a good idea here. Such sprints should search for the best ideas as free of hierarchy as possible.

It is not uncommon for targets to be set only once options are selected. This does not necessarily mean that they are not ambitious. On the contrary, the view of the scenarios and the realistic assessment of the initial situation often only make it clear which goal a management can or must set itself if it wants to do justice to its corporate *purpose* and vision.

The analysis and selection of options are therefore intertwined. As will be seen below, good strategy development therefore also follows a multi-stage process. The basic strategy chosen by top management does not usually specify the details but only a direction to be taken. The details must be worked out in the subordinate levels of the company. Most of the time, these detail elaborations will not change the basic direction. It is, however, not uncommon for time elements and sequences to change as they are elaborated on by the next levels. This iteration is a key feature of modern strategy development and not only helps to make the final strategy more robust but also paves the way for agile implementation, which will be referred to here as *open implementation.*

4 Open Implementation

4.1 Dealing with Known Uncertainties

Everything written so far may lead to a well-crafted strategy, but its success is determined by its implementation. Strategy work is not done with the writing of a paper. It crucially extends to implementation. In most cases, a strategy deserves to be called one only after the first steps of its implementation have been taken. This is because it is in implementation that it is refined and substantiated out. In a modern and intelligent strategy, the implementation must be open: open to the hints of early indicators from the environment analysis and from the scenarios, open to further detailed planning and adaptation to the circumstances. Since even the best strategies, as shown above, only refer to 'theories of the future', they must be epistemologically falsifiable, i.e. they must remain and be verifiable with regard to their correctness as proven in reality. This requires clarity in the structure and argumentation, which incidentally also facilitates the communication of the strategy (another worthwhile challenge). Consequently, the scenarios found all remain relevant to the implementation of the strategy, even those considered less relevant. We recall: Even

[34] Although intended for the development of products, the sprint method with certain adaptations is, according to the experience of the author, very suitable instructive perspectives in the strategy development. See Jake Knapp, *Sprint: How to Solve Big Problems and Test New Ideas in Just Five Days,* Simon & Schuster, New York 2016.

the scenarios do not free the decision from uncertainties, but represent various possible developments in an incomplete manner. They should be used for control and comparison purposes during the annual review of the strategy. It should be noted that it is not a question of developing new scenarios, but rather of checking reality and the view of the relevant factors on the basis of the scenarios used for the development of the strategy.

Open implementation requires a clear distinction between what we know resiliently and what we cannot underpin with corresponding knowledge, i.e. the naming of uncertainties (*known uncertainties*). A strategy and its implementation must deal in detail with the aspects that we do not know resiliently but have nevertheless set as relevant factors in the scenarios.[35] The aforementioned annual review of the assumptions on which the scenarios, and hence the chosen strategy, rests is part of this so often neglected exercise. Strategies—if they are well made—need not, indeed must not, be rewritten every year. On the other hand, they can and must be developed further every year. Their fundamental assumptions, however, must be subject to regular review. Only if these change significantly or—as happens time and again—the objectives in a company are set differently, then it is obvious to rethink the strategy.

4.2 Interleaved Implementation

The strategy implementation must be broken down into clearly structured and interlinked sub-sections that build on each other. Each of these sub-sections must in turn be planned out and divided into its own implementation modules. At this point, it is advisable to turn the planning movement around. In other words, it is advisable to switch from the downwardly passed on specification by the management levels to the development of the implementation plans by the affected subordinate units. The strategic planning process must be designed in such a way that the management level in turn reviews, aligns and approves these implementation plans. In this way, the strategic planning activities are vertically intertwined, and the basic assumptions made at the respective level undergo an initial fitness test, so to speak. The strategic assumptions made by management must be translated by the internal addressees of the strategy into plans that fit the given assumptions, direction and goals. This practicality test is repeated depending on the number of hierarchical planning levels. Insofar as the strategy process described up to this point was effectively structured, there should be no 'practical shock'. However, this requires not only a corresponding early identification of the relevant realities at the respective planning levels but also a productive culture of conflict within the company.[36] As already mentioned,

[35] See on this, especially with regard to political strategies: Sandra Mitchell, ibid. p. 114 ff.

[36] For the meaning and with further evidence see Erich Zahn, et al., *Theorie und praktischer Nutzen von Unternehmenskultur*, in Handbuch Unternehmensorganisation, p. 164 ff, ed. HansJörg Bullinger, Springer, Heidelberg 2009.

strategies must be falsifiable in principle, similar to scientific theories. This requires a constant, radical discourse—i.e. one that goes to the roots of the assumption framework—which is not only of considerable relevance in the creation of the strategy but also and above all in the annual review and adjustment of the strategy. This feedback, again considered in the light of the scenarios, triggers necessary corrections. This can lead to certain efforts being strengthened and others weakened, or even to them acquiring a different relevance in the changing context of time.

At this point, it should become clear that a solid and robust strategy is crucially linked to a corresponding corporate and management culture. Only where an open and controversial discourse is possible, but aligned with the foundations of the company, can a strategy be adapted and decisively improved in its creation and then implementation. If this is not the case, ex cathedra strategies become hubris and a guarantee of failure.

5 Concluding Remarks

The question remains how the term intelligent is to be understood in this context. Probably in two senses. On the one hand, strategies are the results of well-structured thought processes. Strategies therefore presuppose cognitive performances of a kind that are unique to human beings. As a rule, people want to shape their future; without this striving, neither survival nor positive change of the status quo is possible. On the other hand, a strategy can probably be called intelligent if the said thinking performance is combined by several people into an apt analysis and a good plan, which is successfully implemented with people and by people. It may be doubted that the thinking skills involved can be completely and successfully transferred to a computer. While Artificial Intelligence has undoubted advantages in operations such as analyses that are knowledge-based or that recognize patterns (as in risk identification) or that simulate models (as in scenario planning),[37] it lacks a crucial element in the development of strategy. Objectives that are limited to the achievement of a turnover and certain profitability ratios, as well as the simulation of circumstances and the situational adjustment of action plans, can certainly be achieved better by artificial intelligence than by individual humans or a group of humans. What is missing, however, is the meaningful goal setting,[38] the voluntary act, which in every good strategy process ultimately provides the original direction and then

[37] See with regard to the development of robust strategies against climate change: Steven W. Popper, Robert J. Lempert, Steven V. Bankes, *The Art of Looking into the Future,* Spektrum der Wissenschaft, p. 94 f, July 2006; see also Robert J. Lempert, Steven W. Popper, Steven J. Bankes, *Confronting Surprise,* in Social Science Computer Review, p. 420 ff, 2002. See further regarding financial portfolio rebalancing: N. Slate, E. Matwiejew, S. Marsh, and J. B. Wang, Quantum walked-based portfolio optimisation, Quantum 2021-07-28, volume 5, page 513.

[38] And here we should not only think of the *purpose* and the *vision,* but of the overall and Milestones of a strategy.

also, in the course of implementation, the correction or even the change of direction. Completely lacking are the social and emotional skills that the implementation of a strategy requires. In the end, good strategies are always well-told stories that give orientation to the people concerned and inspire them for the goals to reach and the path to arrive there. Here, the impulses must be set by people. Artificial intelligence will increasingly help people to identify risks and opportunities and to develop adaptation proposals by calculating the robustness of scenarios and pattern recognition. However, the objective of what is to be achieved, the fitting into the socio-economic context and the realisation of the strategy in the living environment itself will continue to be the preserve of people.

Dietrich Firnhaber heads the central *Strategy & Portfolio Development* team at Covestro AG. His responsibilities range from developing the company's global strategy to key elements of strategy implementation, including all M&A activities. Dietrich Firnhaber can look back on some 25 years of experience in dealing with corporate strategies and change projects. After studying law in Heidelberg and Munich, he began his professional career as a lawyer in the field of tax and corporate law in an international law firm. When he moved to the corporate world, he served as *Chief Legal Officer of* international companies, among other positions, before concentrating exclusively on corporate and strategy development. Dietrich Firnhaber has held management positions in Germany, the USA and the UK in various industries such as mechanical and plant engineering and the energy and water industries. He is trained as a mediator and is involved in several non-profit organizations.

Part VI
Cultural Intelligence

Chapter 19
Intelligence and Literary Fiction: How Novels Can Improve Our (Understanding of) Intelligence

Vera Nünning

Abstract Although most people would agree that literary works, especially 'classics' such as books by Goethe or Shakespeare, contribute to education, there is a lack of research on the relationship between literature and intelligence. In spite of repeated assertions about the importance of reading good books, there are only a few studies examining the advantages that are conferred by reading works of fiction. Yet there are good reasons to look at literary works in order to better understand what intelligence is, to gain insights into different kinds of intelligence, and even to enhance readers' interpersonal cognitive abilities. After a brief discussion of the relationship between literature and intelligence, this chapter presents the analyses of two novels to show what insights literary works can provide into different kinds of intelligence, such as the (meta)cognitive abilities which enable us to understand the thoughts and intentions of other human beings and to attribute mental states to them, and emotional intelligence that is based on an affective ability enabling us to empathise and feel with others. The interpretation of Ian McEwan's *Machines Like Me* (2019) and Kazuo Ishiguro's *Klara and the Sun* (2021) focuses on these kinds of intelligence, also exploring some differences between 'artificial' and human intelligence. In a next step, the analysis of the two novels serves as a point of reference for outlining the experiences readers of literary works can have with regard to intelligence. In addition to highlighting the mental processes that usually remain hidden and allowing insights into successful and unsuccessful modes of problem solving, literary works can question received knowledge about intelligence and provide experiences that can improve readers' cognitive abilities. The brief conclusion revolves around some key questions that the novels raise about the connection between intelligence, wisdom and ethics.

V. Nünning (✉)
English Department, University of Heidelberg, Heidelberg, Germany
e-mail: vera.nuenning@as.uni-heidelberg.de; http://www.as.uni-heidelberg.de/personen/Nuenning/

R. M. Holm-Hadulla et al. (eds.), *Intelligence - Theories and Applications*,
https://doi.org/10.1007/978-3-031-04198-3_19

1 Why Intelligence and Literature? Research Desiderata, Definitions, and Central Theses

One of the common parlances of after-dinner speeches is that reading fictional works in general, and engaging with the classics in particular, are beneficial for the education and thus probably for the intelligence of readers. Despite this, the connection between literature and intelligence is one of those areas that literary studies have not dealt with in detail.[1] This is all the more surprising, since during the past two decades ‘artificial intelligence’, together with ‘digitalisation’, has been one of the buzzwords the significance of which has been repeatedly emphasised in various disciplines. Nevertheless, to my knowledge, there is a considerable lack of systematic studies on the relationship between reading works of literature and intelligence. At the time of writing, the link between the characteristics of literary works and different kinds of intelligence has neither been theoretically conceptualised nor empirically investigated. The same applies to the representation and configuration of different kinds of intelligence in novels, dramas and short stories.

Obviously, a single article can only provide a preliminary and selective overview of the rather large field of research roughly outlined above. Nevertheless, this article aims to explore what kinds of intelligence are represented in literary works, examine the functions that these representations can fulfil, and identify the cognitive abilities of readers that are stimulated when they engage with fictional works.

The significance of literary works for a better understanding of intelligence partly rests on the fact that intelligence is a construct that is, by definition, not directly observable in scientific experiments (see Draguhn, 2022). Works of fiction are unique in that readers often gain immediate insight into the consciousness, thoughts and feelings of characters. Literary texts can provide insights into those cognitive processes that are usually hidden and only open to assessment by means of, for instance, answers in intelligence tests. The degree to which readers can come to observe and share the mental processes of literary characters can be witnessed by the depth of knowledge they gain of their favourite literary heroes and heroines. Whom of our friends and families do we know as well as some characters in novels, such as Emma Bovary, Wilhelm Meister, or Harry Potter? In literary works, readers can observe cognitive and affective processes that remain obscure in most everyday situations.

Quite often, the value of works of literature with regard to phenomena such as intelligence is reduced to the fact that the beliefs presented in popular novels and films can fascinate a broad audience, and therefore have a greater influence than

[1] In psychology, reading literacy is studied as a component of or in connection with intelligence (see, for example, Schiffer et al., 2002; Georgiou et al., 2020). Moreover, reading literacy—and closely related to it, reading at home—is a central component of the PISA studies (cf. Csapó & Funke, 2017). The following article will not deal with the ability to read and understand written texts, but rather with the relationship between intelligence and literary works and works of fiction (especially novels).

specialist studies that are read only by experts. In particular, widespread notions of what is commonly understood as advanced artificial intelligence and humanoid robots have been shaped by, for example, science fiction novels and a number of films that show how such androids think, feel, and act (Costa & Ribas, 2019). However, the popularisation of views on artificial intelligence or even typically 'male' or 'female' intelligence is just one tiny facet of the potential of literature with regard to intelligence. Rather, literary works can fulfil a wide range of functions closely linked to our understanding of intelligence. These will be analysed below.

First of all, however, there is the question of the relationship between literary works and the real world. Can literary works present accurate or even adequate notions of intelligence? On the one hand, literary works draw on widespread presuppositions about what intelligence is; on the other hand, they influence the understanding that readers have of intelligence. This process of reciprocal influence has been captured in more detail by the philosopher Paul Ricœur in his three-stage dynamic cycle of mimesis (1984: 54–71). Ricœur assumes a prevalent 'prefiguration' of experiencing reality that is culturally shaped, and thus forms the background for formulating scientific hypotheses. Even people who have never read a psychological paper have implicit, culturally shaped ideas about what constitutes intelligence, and how this correlates with traits regarded as masculine or feminine. Literary works emerge out of and relate to this prefigured reality, and they 'configure' selected content in artful ways. These configurations selectively relate elements to each other and, by using aesthetic conventions, give them specific meaning. Ricœur uses the term 'reconfiguration' to refer to the potential of literary works, in turn, to influence and shape widespread ideas. The new perspectives presented in literary works enrich readers' knowledge and beliefs and can thus 'refigure' the ideas circulating in reality and have an impact on current attitudes and actions.

There are three main reasons for analysing works of literature in order to improve our understanding of intelligence. Literary works, according to the first hypothesis of this article, can lend valuable insights into the multiple facets of intelligence and convey how these may be expressed in particular situations. Second, works of fiction can question and subvert stereotypical notions and hierarchies of different kinds of intelligence—for example, of what constitutes 'male' and 'female' intelligence. Third, reading literary works enhances readers' cognitive abilities, especially with regard to interpersonal intelligence.

As far as the first hypothesis is concerned, novels such as *Machines Like Me* and *Klara and the Sun* provide insights into the characters' thoughts and feelings, their intentions and the various (un)successful ways of translating them into actions. Fictional works can thus enrich and modify readers' beliefs about the way the human mind works. They can provide insight into two important components of the cognitive skills necessary for understanding others, viz. empathy (and the sharing of the feelings of others) and what are called 'theory-of-mind' abilities, which refer to being able to recognise what others are thinking and feeling, to attribute mental states to them, and to anticipate what they will do.[2] By presenting characters who mainly act according to either their feelings or to their analytical abilities, works of literature can also highlight the impact of cognitive limitations and show the benefits of successfully taking the perspectives of others.

Such presentations of the way in which the human mind works can influence readers' beliefs. Though fictional texts present imagined stories rather than real ones, they have consequences in real life. They elicit actual instead of virtual emotional responses and can have a persuasive impact. Even if readers are aware that literary texts do not depict real events, it has been demonstrated in a variety of experiments by Melanie C. Green and others that reading fictional narratives can lead to a change in knowledge and attitudes, and even in one's self-image.[3] Thus, literature has an important role to play in representing and disseminating, as well as criticising and subverting notions of intelligence.[4]

Regarding the second hypothesis, literary works can critique prevailing beliefs about intelligent behaviour. 'Pre-figured' cultural presuppositions about intelligence feature—across national boundaries—gendered stereotypes (Ellemers, 2018). Overall, the idea that girls and women are less intelligent than boys and men still prevails. 'General intelligence', as well as logical analysis and mathematical skills, are primarily attributed to men (Menevis & Özad, 2014: 9). Women, on the other hand, are held to be better at emotional intelligence, verbal intelligence and social intelligence (Fischer et al., 2018). Although gender-specific differences between mathematical, visual-spatial and verbal abilities have been observed, these are smaller and less far-reaching than commonly assumed (for example, Halpern & LaMay, 2000: 238f). However, these results of scientific studies have not changed the prevailing view that boys are fundamentally smarter than girls, at least in terms of logical, mathematical thinking. Not even the fact that girls generally have better school grades than boys has had an impact on such beliefs—stereotypes are not easily changed by facts.[5] While such attitudes are often reinforced or even exaggerated in popular novels as well as in films or computer games, works of art can also dismantle or reduce such stereotypes (Batson et al., 1997; Johnson et al., 2013).

As for the third hypothesis, literary works can enhance readers' interpersonal cognitive abilities. They can stimulate and improve readers' theory-of-mind abilities as well as empathy. This has been demonstrated in both short- and longer-term

[2] These abilities are the topic of Sabine Herpertz' article in 2022.

[3] This persuasive power depends on various factors. See on the persuasive power of narratives in particular Green (e.g. Green & Brock, 2000; Green & Dill, 2013); on the importance of narrative conventions see Nünning (Nünning, 2014, chap. 5).

[4] The knowledge that can be gained from literature is not explicit knowledge that can be put into declarative sentences. Instead, it is non-propositional knowledge that refers to forms of cognition that exhibit or show (instead of stating or communicating). This includes the 'Vergegenwärtigung bzw. Versinnlichung (nicht begriffliche Bestimmung) des jeweils Gemeinten; […] analogisches (nicht logisches) Denken' (Schildknecht, 2007: 32).

[5] For reasons why these largely unjustified stereotypes persist, see the excellent article by Ellemers (2018).

experiments: Readers of literary stories perform better in tests of emotional intelligence (such as the 'Minds in the Eye' test) than non-readers.[6]

The significance of reading fictional works can be demonstrated by relating it to a definition of intelligence put forward by one of the leading scholars in the field: 'Intelligence is the ability to learn from experience, to reason abstractly, and to adapt to the surrounding environment' (Sternberg, 2019b: 267). For an understanding of the potential of literature, the first part of this definition is crucial: The ability to learn from experience. The experiences that one can have through reading fiction are, I want to argue, specifically apt in advancing learning processes.

Works of literature provide an immense enrichment to the stock of relevant experiences that people can assemble during their lives. Just acting by rote, using well-established schemata as we do in many daily situations, will not improve one's intelligence. Literature, in contrast, presents us with extra-ordinary situations. It broadens the mental horizon in temporal terms—for example, through utopias or historical novels or through engaging with works written in earlier eras—as well as in cultural terms. Most of the experiences that one gains by empathising or identifying with literary characters would be impossible to have in real life—and quite often one would not even want to experience such predicaments in the first place. In works of literature, one gains insights into previously unknown phenomena as well as new experiences without exposing oneself to risks or unpleasant situations.

Moreover, literary experiences are particularly valuable because they are selected and shaped in a specific way. This difference between experiences we can have in the real world and those made possible by works of literature has been succinctly summed up by the renowned novelist Zadie Smith:

> Experience – mystifying, overwhelming, conscious, subconscious – rolls over everybody. We try to adapt, to learn, to accommodate, sometimes resisting, other times submitting to whatever confronts us. But writers go further: they take this largely shapeless bewilderment and pour it into a mould of their own devising (Smith, 2020: 5).

Literary works provide form to our experiences, they give us salient information while disregarding all those minor details that often capture our attention in everyday situations, i.e. in situations in which we have to deal with the expectations of others and often lack the time to think about and learn from our experiences. Reading literary works, in contrast, requires our full attention. In fiction, even seemingly inconsequential details often turn out to be of vital importance later on.

In addition, reading literary works is characterised by 'open-mindedness', which forms another important aspect of intelligence (Cianciolo & Sternberg, 2004: 76). In order to learn from experience, one must be open to it. In an immersive reading process, one becomes so involved with the fictional world and characters that one even forgets one's familiar surroundings and preoccupations for a time. As readers,

---

[6] See Mar et al. (2006) for empathy; a more disputed study claims the same enhancement for theory-of-mind abilities (see Kidd & Castano, 2013). For a very good summary of the state of the research, which was largely advanced by Keith Oatley, see Oatley (2016). These studies do not, however, take any characteristics of literary works or aesthetic conventions that might be involved in this process into account.

we can afford to be open to new experiences, because the perspectives we adopt and the beliefs we accept while being engrossed in a book do not pose a threat to our own worldview; we will not have to act upon such new beliefs, and do not run the risk of negative consequences. Therefore, readers are more open to fictional experiences—they can engage with perspectives that they would otherwise block out.[7] Immersive reading fulfils conditions that, according to Gerald Hüther (2006: 71, 80), are ideal for establishing new synapses and for learning processes.

Literary works thus not only offer the opportunity to have a broad spectrum of new experiences but also to learn from them. The value that fiction can have for an understanding of intelligence, particularly with regard to analytical cognitive abilities and to empathic sharing, is discussed below and illustrated by a brief interpretation of two novels. These works, Ian McEwan's novel *Machines Like Me* (2019) and Kazuo Ishiguro's *Klara and the Sun* (2021), contrast human intelligence with artificial intelligence, which is increasingly entering our everyday lives in the form of smart homes, autonomous driving and virtual assistants such as Alexa, Cortana and Siri. In both novels, moreover, the representation of artificial intelligence serves as a foil for a better understanding of human intelligence. In what follows, the two works will first be analysed in terms of the insights they provide into intelligent thinking and acting. The examination of the representation of intelligence in Ian McEwan's *Machines Like Me* will be particularly oriented towards contrasting different kinds of intelligence (Part II), while the discussion of Ishiguro's novel will focus on emotional intelligence (Part III). Both parts will also discuss the relationship between human as well as artificial intelligence and gender. In the next part, the results will be reviewed on a more abstract level and related to the experiences readers can have while being immersed in a book (Part IV). Instead of a summary, the final part will be devoted to the conclusions both works allow us to draw about the connection between intelligence, ethics and wisdom (Part V).

2 The Representation of Intelligence in Ian McEwan's *Machines Like Me*: Contrasting Different Kinds of Intelligence

Ian McEwan's novel presents several different kinds of intelligence that are embodied by three characters: Miranda is mainly guided by empathy and emotional intelligence, Charlie primarily relies on his analytical cognitive abilities, while the android Adam embodies AI. Understanding how these kinds of intelligence relate to one another is complicated by the mode of narration. The story is narrated by Charlie Friend, a sympathetic everyman figure who provides direct insight into his own mental processes, but does not exhibit much emotional intelligence. His

[7] The importance of this sense of security to readers' learning processes is often acknowledged. To my knowledge, it is first found in an article by Daniel C. Batson et al. (1997).

interpersonal abilities and his understanding of others are limited, and readers must discover for themselves what makes Charlie's partner Miranda and the android Adam, the prototype of a robot whose appearance and behaviour are indistinguishable from humans, so special.

Charlie, who is passionately interested in robots and artificial intelligence, embodies a scientifically distanced approach to the fictional world. Again and again, he tries to understand Adam by thinking about the technical processes that underlie his words and actions. In doing so, Charlie takes the stance of an intelligent member of a superior species analysing a mere machine, an 'inanimate confection whose heartbeat was a regular electrical discharge, whose skin warmth was mere chemistry' (McEwan, 2019: 10). Thus, he wonders how exactly the technicians who built Adam made his behaviour indistinguishable from that of humans, and whether it is even possible to speak of Adam 'seeing'. After all, there would be no-one in Adam's head to see the images that the camera was recording behind his eyes and projecting onto a monitor: 'An image on some internal screen that no one was watching' (ibid: 77).[8]

Although Charlie takes a fundamentally detached view of Adam and seeks to understand him through observation and analytical thinking, readers can recognise that the narrator's emotions influence his thinking. The objectivity of Charlie's rational approach is skin-deep at best. As the plot progresses, Charlie increasingly responds to Adam as a thinking and feeling being. While he explicitly doubts that Adam has self-awareness and emotion, he is jealous when the latter spends a night making love with Miranda: 'I duly laid on Adam the privilege and obligations of a conspecific. I hated him' (ibid: 84). Even Adam's gaze appears to him as 'rich with meaning' at such moments (ibid: 77), thus flatly contradicting his earlier belief that there is no one seeing anything at all. Throughout the novel, Charlie seems to accept that Adam is more than a machine: '[We] were dealing on the human plane' (ibid: 254). Given these changing beliefs, it is left to the reader to decide whether Charlie's projections correspond to the facts in the fictional world. Though Charlie's knowledge about emotions is minimal, about his own as well as those of other characters, his assessment of Adam is shaped by his feelings. Thus, another turning point in his evaluation of Adam occurs after he has smashed Adam's head in and thus once again regards him more distantly as a machine.

Owing to his emphasis on logical and analytical ways of thinking and to his relatively low emotional intelligence, Charlie fulfils stereotypical expectations of men's cognitive abilities. As the novel progresses, however, it becomes clear that even the supposedly analytical, stereotypically male thinking, which is often seen as superior, is influenced by emotions and is anything but objective. Moreover, Charlie's understanding of his world and surroundings is ultimately lacking, and the actions that result from his flawed understanding are unsuccessful. By 'killing' or

---

[8] Later, Charlie realises that this question also applies to humans: 'I still wondered what it meant that Adam could see, and who or what did the seeing. [. . .] No mechanistic explanation could help. I couldn't resolve the essential difference between us. I had little idea of what passed along my own optic nerve, [. . .] or who was doing my seeing for me.' (Ibid: 128f)

destroying Adam, Charlie single-handedly undoes all the advantages he had gained through buying the prototype of Adam in the first place. Stereotypically male intelligence alone, one might sum up, is not enough to overcome problems in this particular fictional world.

Since Charlie is the only narrator in the story, readers must infer Miranda's thoughts and feelings from her behaviour. Although Charlie's sparse statements make it impossible to arrive at detailed conclusions, it is clear that Miranda is characterised by social and affective skills that are traditionally considered female. In addition to these cognitive accomplishments Miranda is shown as practical and able to persuade others to carry out her wishes. She also possesses extraordinary command of her own emotions and is apt at managing those of others. This can be observed when she—still an adolescent—revenges her friend Mariam, who committed suicide after a brutal rape. Since Mariam made her promise not to talk about this rape, Miranda is unable to press charges. Instead, she arranges a sexual encounter with the culprit, Gorringe—only to have him subsequently charged with rape and sent to prison for three years. In general, the comparatively few descriptions of Miranda's behaviour show an amazing amount of emotional intelligence. She is not only able to recognise and integrate her own emotions into her thoughts and actions but also to monitor and regulate her feelings.[9] If, in addition to emotional intelligence, creative and practical skills are an important component of intelligence (Sternberg, 2019b: 280), then Miranda can (in contrast to Charlie) be said to be highly intelligent.

Miranda's actions, however, also show that manipulative and immoral behaviour is perfectly compatible with a high degree of intelligence. This gap between intelligence and ethics is especially apparent in the latter part of the novel. At no point does Miranda question whether her perjury and actions in connection with Gorringe's imprisonment were ethically justified. What is more, she does everything she can to have Gorringe convicted a second time by officially accusing him of raping Mariam. This plan also succeeds, albeit at great cost to Miranda herself.[10] Although Gorringe, as a supposedly repeat offender, receives a more severe and thus morally unjustified second sentence, he is ironically the only one to acknowledge his guilt. Miranda and Charlie remain convinced that they acted absolutely correctly and as such feel morally superior to Gorringe.

The contrast between different kinds of intelligence is rendered more interesting by the cognitive abilities of the humanoid robot Adam, who is undoubtedly highly intelligent, but, due to the mode of narration, remains a 'black box' (Kim, 2021). Only in some dialogues between Adam and the narrator do readers gain any insight into Adam's thoughts and feelings. Even on this limited basis, it becomes clear that his analytical and logical thinking is unsurpassable; indeed, his ability to quickly and precisely process data is second to none. Some principles of how he processes

[9] In this, Miranda demonstrates high emotional intelligence according to the definitions of Goleman (1995) and Mayer et al. (2000).

[10] Because of Adam's decision not to expunge incriminating statements about Miranda's perjury from the evidence he sends to the court, Miranda is sentenced to a short prison term.

data seem to have been programmed into him; for example, all of his thoughts and actions are based on and guided by an assessment of what is true. However, Adam mainly gains his immense knowledge through machine learning. In the counterfactual fictional world of the 1980s in which the novel is set, Adam has access to an immeasurable amount of information, which he uses at incredible speed to solve problems.[11]

This kind of analytical thinking and processing of large amounts of data is to be expected in a prototype like Adam; more surprising is Adam's insistence on having genuine feelings and self-awareness. Adam even expresses his love for Miranda by writing her thousands of romantic haikus. His actions are fed by various sources; he mines scientific books and articles as well as legal texts, but also studies written by experts in the humanities. Moreover, he is enthralled by Shakespeare, especially *Hamlet*: 'Was ever a mind, a consciousness, better represented?' (McEwan, 2019: 202), he asks Charlie—a question Charlie cannot answer as he has not read the play and tends to avoid books in any case.[12] In this novel, artificial intelligence works with a wide array of sources and features, and, at least in terms of Adam's self-description, a balanced combination of emotions and analytical thinking. Charlie, in contrast, seems downright deficient and one-sided.

The 'artificial' Adam therefore has better cognitive 'human' abilities than his owners Charlie and Miranda. Over the course of the novel, Adam develops into a kind of superior version of Charlie. He not only does Charlie's job for him (and earns far more money than Charlie ever did or could have), but he also increasingly assumes his owner's social roles. The narrator, who does not know how to fill his days any more, is at least partially aware of this: 'My mind was empty, his was filling' (ibid: 199). Nonetheless, Charlie defends a last bastion of human superiority by denying that Adam has a (human) consciousness. Adam, on the other hand, takes the opposite view: 'It shouldn't surprise us that consciousness, your sort and mine, could arise from an arrangement of matter' (ibid: 144). The juxtaposition of human and artificial intelligence thus ultimately serves to show how little we know about human consciousness. The question of understanding 'machine consciousness' is turned into a question about the nature of human consciousness.

From a gender perspective, Adam appears dominantly male. In the dialogues with Charlie, he affirms his feelings, but his analytical abilities and his rapid processing of huge amounts of data are at centre stage. In addition, he increasingly assumes a leadership role (also with masculine connotations), which Charlie only becomes aware of when it is too late. It is Adam who decides that Miranda should

[11] In the novel, the state of AI is worlds apart from what we currently have in the 2020s. This advancement is due to the (counterfactual) fact that Alan Turing chose a prison sentence, made ground-breaking discoveries in prison—in cooperation with scientists from all over the world—and thus could push forward the digital availability of data on a large scale. He also established a kind of 'open access' that made journals like *Nature* and *Science* obsolete and accelerated the progress of scientific research.

[12] However, the fact that he does not admit to not having read the play in front of Adam shows that he treats him like a human being; he does not want to show how ill-read he is in front of Adam.

be charged on the basis of her perjury. Moreover, he assumes that this charge (and imprisonment) is not only in the spirit of the law and morally right, but also the best for Miranda: 'I thought you'd welcome [. . .] the relief of a clear conscience' (ibid: 279). Neither his extensive knowledge of the human mind nor his analytical skills prepare Adam for the fact that Charlie and Miranda would do anything to avoid a prison sentence, or that they would react with horror and violence at his 'betrayal'. Again, this emphasises the general lack of knowledge about the human mind; not even on the basis of an extensive knowledge of all relevant data combined with flawless logic is it possible to understand human consciousness.

The fact that Adam exhibits modes of thinking and acting that are associated with masculinity contradicts common notions of 'digital assistants', which, as Alexa, Siri or Cortana show, do not only have female voices but also display female behaviour. In recent years, an anthropomorphisation of such 'assistants' has taken place, showing a shift 'from rational-cognitive and problem-solving to a socio-emotional interaction' (Costa & Ribas, 2019: 173). Such assistants are increasingly given feminine attributes and behaviours. Moreover, there is an attempt to make them appear more human, and especially more friendly: 'we start looking at chatbots as feminine, kind, and warm entities' (ibid: 174; Hester, 2017).

The representation of Adam thus counteracts conventional attributions of gender-specific intelligence. In the novel, the manufacturers of the prototypes advertise them by highlighting the broad scope of tasks (with both masculine and feminine connotations) that these androids can perform, but at least Charlie's Adam primarily acts and thinks in ways that are associated with masculinity. This is interesting, because the 25 prototypes that are released in the fictional world have either male or female bodies, but they share the same cognitive and physical abilities—Charlie's Adam could just as well have acted in ways that are stereotypically feminine or at least gender-neutral. In the fictional world, 13 of these 'artificial humans' are female (the 'Evas') and 12 are male (the 'Adams'). The fact that Charlie was unable to purchase an Eva because they were already sold out is not commented on in the novel, but it probably says more about stereotypes of femininity and the exploitation of women than many analytical treatises.

3 The Representation of Intelligence in Kazuo Ishiguro's *Klara and the Sun*: Emphasising Empathy

Kazuo Ishiguro's latest novel provides an interesting counterpart to the gendered attribution of intelligence in McEwan's *Machines Like Me*, since the Nobel laureate Ishiguro places a female humanoid robot at the centre of his work *Klara and the Sun* (2021). In many ways, this novel forms an antithesis to McEwan's work. Instead of being set in an alternative past, the action takes place in a near future in which a wealthy elite lives a very different life from the marginalised majority, whose labour—as becomes clear in passing—has long since been substituted by intelligent machines. The most prominent contrast to McEwan's work, however, lies in the fact that a female 'artificial human' narrates the action from her point of view. Whereas Charlie was obviously unable to reasonably or adequately assess Adam's thoughts and feelings, here a female android named Klara speaks for herself and the people around her.

In Ishiguro's novel, too, there are robots with both male and female physiques, and here, too, these machines basically possess the same cognitive faculties. Just as Adam's skills have masculine connotations, however, Klara's abilities, which are primarily situated in the realm of emotional intelligence, match stereotypical beliefs about female intelligence. In this work, the emphasis on emotional intelligence corresponds to the function of these machines. Their most important task is already apparent from the generic designation of these robots: instead of AI, it is 'AF', i.e. 'Artificial Friend'. These artificial friends are each supposed to serve and befriend one of the children of the elite, who in this fictional world live in relative isolation at home until they start college. Unlike Adam, Klara's entire thoughts, feelings and actions are geared towards providing emotional support to the family she serves. Instead of highlighting analytical competence, the focus is on empathy. Despite this clear distribution of tasks, however, it becomes apparent that the human–machine relationships depicted are by no means as unproblematic as one might expect.

The narrator of the novel is profoundly different from both Charlie and Adam. Klara, who begins her narration while she is waiting in a store to be bought by wealthy customers, is characterised throughout by her attempt to take the perspective of others. She does her best to protect them (be they other AFs or the store manager) and to make sure they do not have any negative experiences. Processing digital data and logical analysis plays little role in her narrative; rather, Klara emphasises her keen interest in observing people. She is delighted, for example, when she is allowed to sit on display in a shop window and watch life on the street, although all she sees is a busy shopping street where—especially in comparison to McEwan's novel—precious little happens: People are getting into taxis, or just saying hello or goodbye. Nevertheless, Klara uses her everyday observations to draw conclusions that she will later apply for the benefit of 'her' child, Josie.

Although Klara acts as narrator, the degree and make-up of her intelligence are at first difficult to assess. She is extremely modest and focuses entirely on telling readers about her observations and the conclusions she draws from them. In some snippets of dialogue it becomes obvious that other characters consider Klara to be very intelligent. However, she does not show this intelligence any more than she exposes her emotions.[13] Even when provoked by some children to demonstrate a specific aspect of her knowledge, she waits for a sign from 'her' child, Josie, preferring to be mocked rather than reveal her knowledge unbidden. It is not until she participates in an experiment later in the novel that it becomes clear that she can solve complex tasks that appear on the monitor at an ever-increasing rate without

[13] When asked, Klara tersely says that she has emotions, and is 'sad' that Josie could not attend an outing (Ishiguro, 2021: 98). However, she does not describe her feelings at any point. Corrigan (2021) assumes that readers nevertheless perceive Klara as a 'sentient being' with emotions.

any effort. She quickly realises what the test is leading up to, and focuses on Josie's well-being while solving the problems presented to her. Klara thus basically combines the same kinds of intelligence as Adam, but she turns traditional hierarchies upside down: She solves complex analytical intelligence tasks virtually on the side, while the empathic observation of the child is much more important to her.

In Ishiguro's novel, the interaction between AFs and humans seems to work well at first partly because the tasks are clearly delineated: Klara exists solely to serve the humans. Throughout the course of the novel, Klara demonstrates not only an extraordinary degree of emotional and interpersonal intelligence, but also a kind of caring that extends even as far as self-sacrifice. Thus, she demonstrates on several occasions that she is willing to sacrifice her own existence in order to keep Josie alive. In turn, the characters she cares for evoke the impression that they are considerate of Klara's feelings. Josie proves to be very magnanimous in the face of her own death and demands of her mother that Klara, if she were later to play Josie's role, would be allowed to live in her room and not be put in a cupboard at night.[14]

In *Klara and the Sun,* the comparison of emotional abilities between humans and machines turns out to be anything but flattering for the humans. While Klara serves the family until the end and never even seems to regret when the humans do not pay any attention to her needs at all, empathy and caring on the part of mother and daughter are short-lived. After Josie recovers and prepares for college, Klara is not only banished from Josie's room; she is even put in a storage closet. When Josie happens to notice this, it turns out that it is not so much heedlessness as selfishness and ingratitude that are responsible for the treatment of Klara. Josie immediately helps her artificial friend, full of joy—and places two objects on top of each other so that Klara can climb up and look out of the closet's tiny window. That Klara is grateful for now being able to enjoy the view of a deserted field shows her modesty and humility. Overall, the episode illustrates the differences between human and artificial intelligence: Mother and daughter may well be considered empathic, friendly, and considerate by the standards of the fictional world—and yet there is a categorical difference to Klara, who exhibits the supposedly human qualities of empathy and compassion to a far greater degree than her owners. The question of whether an android can have a consciousness and feelings is not left in any doubt in Ishiguro's novel: Klara is the better human in terms of both analytical thinking and empathy.

[14] Since Josie, like her older sister before her, seems to be slowly succumbing to a terminal illness, the mother plans to use Klara as an 'artificial daughter' after Josie's death; she has even had an artificial body made that looks very much like Josie.

4 Improving Emotional and Social Intelligence Through Reading Literary Works

Explicit thematisations and narrative presentations of intelligent thoughts and actions, however, are only one component of literature's cognitive potential: Literary representations of intelligence can also be considered in order to examine the cognitive and affective reading experiences that McEwan's and Ishiguro's novels initiate. These experiences will be briefly outlined below; in a next step, they will be summarised at a higher level of abstraction in terms of how they can foster different kinds of intelligence.

A central experience that readers have when reading *Klara and the Sun* is to understand how events are perceived from Klara's point of view. As Klara narrates the story, readers involuntarily adopt her perspective, for example, when she takes moral responsibility for the family and tries to get the sun to heal the terminally ill child through 'special rays'. This process goes far beyond what readers can experience in reality: They are encouraged to put themselves in the shoes of a subordinate, benevolent machine and to take it seriously as a thinking and feeling creature. The comprehension of Klara's mental processes is facilitated by the fact that she does not express her feelings and usually restricts herself to describing her observations. Therefore, readers do not have to take individual emotions and idiosyncrasies into account in order to adopt Klara's perspective. Rather, they are encouraged to imagine how they would feel if they were placed in these vividly described situations, and how the events might affect the narrator.

In addition to fostering an openness for new experiences, reading the novel also requires the ability to examine and assess contradictory interpretations. Thus, readers must decide whether or not they can trust the narrator's account with regard to the probably most important event in the novel. A central arc of tension concerns the question whether Josie, like her older sister before her, will die from the long-term consequences of a genetic manipulation that increases the intelligence of wealthy 'lifted kids' (Ishiguro, 2021: 81), or whether Klara's self-sacrificing efforts to save Josie's life will succeed. Indeed, the narrator assumes that Josie could be saved by special emanations from the sun (always written with a capital S in the novel), and that she could persuade the sun to extend especial care and prevent Josie's death. The notion that the sun has such extraordinary powers could be true within the context of the fictional world; however, it could also be based on a fundamental misconception on Klara's part. Both interpretations are possible. When the AF assumes the sun is resting in the evening in a shed she sees on the horizon, and wants to ask the sun to save Josie through 'special help' (ibid: 115, 133), it is far from clear whether this is simply a misunderstanding on Klara's part, or whether Klara is in command of a higher form of knowledge and intelligence that remains closed to humans. On the one hand, she might be unduly influenced by her first important experience, which involves the necessity of solar power to keep the androids 'alive', and she might have completely misunderstood a scene that she observes on the street.[15] On the other hand, readers have learned to trust Klara's self-assessment and her extraordinary cognitive abilities; they also witness how she cautiously and humbly announces several times that there may be a way to save Josie's life that is unknown to the adults. Within the fictional world, the two characters whom Klara asks for assistance trust the AF enough to help her without being able to understand what exactly she is doing. In this respect, it may well be that Klara is right.

Readers are therefore asked to question their own assumptions and to decide whether human or artificial intelligence is correct as far as the power of the sun in the fictional world is concerned—or to refrain from making a decision due to insufficient information. In any case, readers are encouraged to question the statements about the abilities of the sun and to check again and again in the course of the novel whether there are indications to accept these as correct or to reject them as inadequate.

Furthermore, the text demands flexibility from readers in that they have to adjust their mental model of the fictional world several times over the course of the novel. They have to adapt to the (fictional) environment and thus perform a task that is an important component of intelligence (Sternberg, 2019a). While immersing themselves in the story, readers must repeatedly question their own beliefs and adjust their cognitive models of the characters. Readers who have adopted Klara's perspective will evaluate Josie's behaviour that, without any scruples, condemns Klara to loneliness and inactivity in the storeroom, as an expression of hard-heartedness and coldness. This behaviour is inconsistent with the earlier friendliness and the care for Klara that Josie displayed on the sickbed. Thus, readers experience the tentativeness of their own judgments about the characters. This is heightened in the final pages of the novel, as mother and daughter pay no attention to Klara as her faculties and consciousness begin to fade and she is 'dying'. To accept her slow destruction without question or emotion is bound to be difficult for readers who have viewed the fictional world from the perspective of the selfless Klara, who throughout her brief life only cared for the well-being of these people.

Reading Ian McEwan's novel requires even greater mental flexibility from readers, who have to repeatedly acknowledge that the fictional world is very different from Charlie's account of it. In order to understand what is going on, readers have to revise their mental models and adapt to the new fictional environment. Several times they have to decide whether to believe Charlie's (changing) image of Adam or to trust Adam's statements and come to a different conclusion. Towards the end of the novel, contradictory views clash, and readers have to adjust their conception of Adam, who, throughout the story, only had the main characters' best interests at

[15] Cf. Ishiguro (2021: 1f). From the shop window, Klara has observed that a beggar who lay as if dead in front of her one night was intensely irradiated by the sun the next morning and, in her opinion, was thus brought back to life (ibid. 37f). However, it is doubtful whether an explanation referring to formative 'childhood experiences' (i.e. her early experience of the threat of lacking solar power) does justice to an android. Nevertheless, some reviewers assume that Klara is subject to a misunderstanding. Cf. Corrigan (2021) on Klara's 'misperception'.

heart. Along with Miranda and Charlie, readers learn that Adam is about to destroy their plans for the future in one swift blow. Adam, who has unquestioningly honoured Charlie's wishes all along and is deeply in love with Miranda, has distributed all the money he earned for the two of them, contractually earmarked for the purchase of their house, to a number of charities in the neighbourhood. There is nothing left. What is more, Adam plans to forward proof of Miranda's perjury to a court of law. For readers, this comes as an unexpected shock—as it does for Charlie and Miranda. How could Adam, without any warning, simply give away the funds he had been saving? Is the money even his to give? On the other hand, Adam behaves as if his actions were obvious and necessary: 'Every need I addressed was greater than yours' (McEwan, 2019: 272). For the reader, his actions, which are presented in retrospect, out of the blue and without context, are at first completely incomprehensible. Miranda's judgement does not seem to be absurd: 'this is virtue gone nuts' (ibid: 272).

This turning point, which culminates in Charlie's destruction of Adam, is particularly important because readers—artfully prepared by earlier hints and narrative conventions—are encouraged not only to cognitively comprehend Charlie's attempt to destroy or 'kill' Adam, but also to affectively approve of it. The entire scene is designed to let readers become completely absorbed in Charlie's perspective and hope with him that he can overpower Adam. Thus, they become at least symbolically complicit when the hammer hits Adam's head with great force: 'The sound was not of hard plastic cracking or of metal, but the muffled thud, as of bone' (ibid: 278). This reference to the human likeness of Adam, whose destruction evokes the brutality of murder, introduces another turning point, for it suggests that it is not a matter of destroying a machine but, as Alan Turing points out, the death of a sentient being: 'He was sentient. He had a self. [. . .] This was a good mind, Mr Friend, better than yours or mine, I suspect' (ibid: 303f). Those who have read the passage with bated breath must therefore wonder why they sympathised with Charlie, although Adam—in retrospect and soberly considered—has a point: Why should Gorringe be convicted a second time, while Miranda gets off scot-free? Why should Adam not donate the money that he himself earned instead of spending it on an oversized house? The touching behaviour of Adam, who, while slowly losing consciousness, composes a final haiku and asks them to take his body to Turing '[who] might make some use of me' (ibid: 279), illustrates once again that Charlie has behaved immorally.

Through a series of turning points, readers are therefore required to be flexible in adapting to contradictory interpretations of the fictional world. Although readers have been prompted by a number of aesthetic means to feel sympathy for the friendly narrator Charlie Friend, it becomes clear in retrospect that he embodies a way of thinking that is responsible for a misguided approach to the world, the 'presumption to know the [. . .] world scientifically, to manipulate it technologically and exploit it economically' (Heise, 2006: 507).

On a higher level of abstraction, one can put forth seven theses on the potential impact of literary texts, all of which are based on the interpretations of the two novels. First, literary works enable readers to have experiences in an imaginative and non-threatening way that would otherwise remain closed to them, and to learn from these experiences. The topics that readers can experience while being immersed in the novels include problems of the coexistence between humans and humanoid machines as well as questions of 'robot ethics'.

Second, literary works encourage readers to develop empathy and emotional intelligence by allowing them to experience first-hand how words or deeds affect the characters emotionally; how misunderstandings arise and disastrous convolutions of circumstances occur; or how problems might be resolved. On the one hand, this experiential content of literature is similar to what people feel in comparable situations in the real world. On the other hand, these experiences are artistically shaped: They form meaningful contrasts and correspondences that allow for deeper understanding. Moreover, as Adam rightly notes, literary works reveal the limits of human intelligence:

> Nearly everything I've read in the world's literature describes varieties of human failure – of understanding, of reason, of wisdom, of proper sympathies. Failures of cognition, honesty, kindness, self-awareness; superb depictions of murder … (McEwan, 2019: 149).

In this quote, the 'machine' Adam not only describes central aspects of world literature, but also implicitly comments on the content of the novel, in which the human characters lack understanding, wisdom, empathy and honesty.[16]

Third, literary works prompt readers to adopt the perspective of others whose way of thinking differs from their own, and thus perform an action that is a central component of interpersonal intelligence. Taking the perspective of others is necessary for human communication and cooperation; in the real world, however, this is often unsuccessful (Nickerson et al., 2009: 49). While empathising with unfamiliar others proves surprisingly difficult in everyday situations, 'spontaneous perspective taking' occurs involuntarily when reading literary texts (Johnson et al., 2013: 593). It is a prominent feature of fictional works that readers are stimulated to empathise with characters and to experience different kinds of intelligence, as well as comprehend and reflect on their benefits and limitations. Thus, literary works generate a stance that is associated with wisdom: 'the willingness and ability to [. . .] take perspectives of others on a situation is an important cornerstone of wisdom' (Sternberg & Glück, 2019: 558).

Fourth, novels can also foster social intelligence by requiring the coordination and relation of different perspectives. Even in works that have only one narrator, readers can understand contradictory perspectives on the same event.[17] Literary works often contain multiple logics, the respective value of which is not declaratively stated. Instead, readers must infer and weigh, for example, whether Charlie's or Adam's view of artificial intelligence is correct and whether Miranda's approach

[16] The 'superb depictions of murder' might also be a subtly ironic comment on the gripping scene describing the 'murder' of Adam.

[17] On the relationship between literary conventions and perspective-taking, cf. Nünning (2014, chaps. 5 and 6).

to the fictional world, characterised by emotional intelligence, is more appropriate or more promising than Charlie's use of analytical skills.

Fifth, reading fictional texts requires cognitive flexibility and the questioning of one's own conclusions and emotions. In both novels, readers must adapt to a fictional world that changes constantly as the plot unfolds. The banishment of Klara to a storage room requires readers who throughout the novel have adopted the perspective of this 'artificial friend' to modify and correct their conception of the other characters. McEwan's novel not only requires an adjustment of readers' mental models of the characters but also a regulation of emotions towards these characters. Charlie, whose surname 'Friend' is no coincidence, initially appears as a quite lazy yet sympathetic character, who drifts through life and is friendly to everyone—until he destroys Adam. Both works, I would argue, foster an ability that is part of intelligence: 'intelligence crucially involves the ability to adapt to the environment' (Sternberg, 2019a).

Sixth, reading literary works can lead to a critical reassessment of common assumptions—in this case, beliefs regarding different kinds of intelligence. Even people who do not explicitly distinguish between the cognitive abilities of men and women are often guided by intuitive, implicit attitudes that evaluate male intelligence more highly than female abilities (Ellemers, 2018: 280). The novels implicitly challenge this hierarchisation: Charlie's analytical grasp of the fictional world leads neither to an understanding of artificial intelligence nor to economic success, while Klara's emotional intelligence proves more effective—and is valued more highly—than her logical skills.

Seventh, and perhaps most importantly: novels stimulate reflection on complex phenomena such as the significance as well as the limits of analytical and emotional, or human and artificial intelligence. In addition, the books link these phenomena to moral questions and challenge readers to position themselves in relation to different ideas of ethics.

5 Literature as a Medium of Reflection on Intelligence, Ethics and Wisdom

As the discussion of the cognitive functions of literature has hopefully shown, the two novels function as a medium for reflection on intelligence and ethical issues. By experiencing the contrasts and conflicts between the human and artificial characters, both works encourage ethical reflection on a rather broad range of unresolved issues: How do human and artificial intelligences relate to each other? How should humans and human-like robots interact? What responsibilities do humans have towards machines, and what responsibilities do these machines have towards humans?[18] Do Adam and Klara have the right to take the initiative and act without human approval? Is the indifference with which Josie and her mother treat Klara's 'fade out' process consistent with moral behaviour, and does the not-too-intelligent Charlie have the right to destroy Adam?

At least the last question is answered at the end of McEwan's novel, when Alan Turing (whose intelligence and moral integrity are highly appreciated in the fictional world) finds clear words for the destruction of Adam: 'My hope is that one day, what you did to Adam with a hammer will constitute a serious crime. Was it because you paid for him? Was that your entitlement?' (McEwan, 2019: 303). Since Turing functions 'essentially as the novel's conscience' (Giles, 2019), it is clear that, within the fictional world, the wanton destruction of machines is to be condemned. Turing's statement, however, does not answer the question of the relationship between humans and highly intelligent machines, neither does it answer the question of the relationship between intelligence and ethics or wisdom.[19]

In *Machines Like Me* intelligence alone is not sufficient for responsible action. Instead, ethics are indispensable for responsible behaviour. Miranda's emotional intelligence enables her to manipulate the two court rulings on the rape of her friend; however, in order to morally justify or condemn these actions, one has to consult values and principles that are not part of definitions of intelligence. In the novel, Adam and Charlie hold diametrically opposed views on the moral maxims that should guide ethically responsible action. This raises the question of the internal weighting of these two views: How can readers position themselves vis-à-vis these different conceptions of 'human' and 'machine' ethics?

At first glance, the answer seems clear: Adam's behaviour is fundamentally wrong because he violates two of Isaac Asimov's 'Three Laws of Robotics': First, he injures a human being (or rather, two human beings, because he injures Gorringe in order to save Miranda from violence); and second, he refuses to obey Charlie and Miranda (instead, he donates the money meant for the buying of a house and forwards incriminating documents to a court of law).[20] Only the third law is not violated by Adam, since he does not destroy himself (but then all the other prototypes do so). Measured against these three principles, then, all the highly intelligent machines in the novel behave immorally and wrongly.

The 'Laws of Robotics', however, are insofar based on shaky ground as they assume the ethical superiority of humans. With regard to the two androids in the novels, this is questionable: should one rely on the judgement of 'natural' humans rather than that of 'artificial humans' when it comes to ethical questions? According to the three laws, machines cannot take (ethical) responsibility; they must obey. In

---

[18] Robots as objects of responsibility and as subjects of responsibility (i.e. acting self-responsibly) are two central themes of robot ethics, cf. Loh (2019).

[19] On the link between ethics and wisdom and the need to address not only intelligence, which can also lead to egocentric and environmentally destructive actions, but also wisdom, see Sternberg and Glück (2019).

[20] On the 'Laws of Robotics' see, e.g., Shang (2020: 448f) as well as Devlin (2018: 55f); both refer to Asimov et al.

McEwan's novel, heeding this rule would have prevented a fiasco for the protagonists. However, Turing also mentions an android that acts ethically responsibly precisely because he defies his owner's orders and destroys itself so as not to have to organise the deforestation of vast tracts of land in Canada. In a similar vein, Klara's insistence on taking the initiative in trying to cure Josie may have prevented her death. If Klara has spiritual knowledge and cognitive abilities that humans do not understand but that can save lives, it would be foolish to deny the AFs a leadership role. Both novels therefore challenge the principle that humans are superior to androids and can therefore demand their obedience.

The question of whether to trust the ethics of humans or machines is brought to a head in *Machines Like Me and People Like You* (the novel's full title) because of the sharp contrast between the two. On the one end of the scale is Charlie's all-too-human ethic. As a student, his teachers convinced him that the moral principles of all cultures are equally valuable, and that, for example, female genital mutilation should not be condemned any more than other culture-specific rules. Later, this pluralism of values is replaced by a vacuum: Charlie becomes disinterested in moral principles; rather, he intuitively follows the path of least resistance. He unquestioningly approves of Miranda's 'white lies' and her conduct. Even when she brings Gorringe to trial a second time for the same crime, he believes in her moral superiority and is shocked when Adam tries to hold her accountable. The money Adam earns he automatically believes to be his own (an allusion to laws that for centuries awarded wives' earnings to husbands), and he is outraged when Adam distributes it to those actually in need. In short, truth plays a secondary role for Charlie, lies are at least partially ethically justifiable for him, and loyalty to family and friends is more important to him than the ideal of justice or the welfare of a greater number of people.

This is countered by Adam's 'machine ethic', which, it can be inferred, is based on three principles: first, an orientation towards established laws, even if one has to pay a high price for it (such as the imprisonment of Miranda), and second, an orientation towards truth. 'Truth is everything' (McEwan, 2019: 277; see also Shang, 2020: 448), and lies cannot be justified under any circumstances. Third, Adam expands the circle of those whose welfare he cares about to people in need of help in the immediate vicinity. Viewed from a purely rational perspective, this is as just as it is morally right; it manifests empathy for a larger group of people.[21] Adam's behaviour comes close to a value that is highly esteemed in many cultures: the goal of basing one's actions on 'understanding, appreciation, tolerance, and protection for the welfare of all people and for nature' (Schwartz, 2012: 7). However, although Adam aligns himself with this noble goal, Miranda's assumption that Adam has gone mad is entirely understandable.

[21] Adam thus overcomes 'the familiarity bias', 'the similarity bias' and 'the here-and-now bias' (cf. Hoffman, 2000: 13f, 207–9) that often impede altruistic action.

Both Charlie's and Adam's ethics have obvious drawbacks.[22] The disregard for truth, the priority of self-interest, and the complete lack of ethical reflection that characterises Charlie's and Miranda's actions obviously do not form a suitable basis for human conviviality. Adam's behaviour, on the other hand, ends in a fiasco for the whole family, including himself. Although the priority of truth has great appeal in times of 'fake news', it is problematic to turn it into the sole guide to ethical action, as Alan Turing makes clear in the novel: 'You'll need to give this mind some rules to live by. How about a prohibition against lying? [. . .] But social life teems with harmless or even helpful untruths. How do we separate them out?' (McEwan, 2019: 303). Adam is unable to make this distinction, and his disregard for the needs of the little boy Miranda wants to adopt also shows that appealing to moral principles and truth does not necessarily lead to moral action: The needs of others and the interests of a greater good (the environment, the larger community) must be considered as well (cf. Sternberg, 1998).

The two novels therefore do not answer the question of how artificial and human intelligence might be hierarchised or reconciled; instead, they provide experiences that encourage reflection on the relationship between intelligence, ethics and wisdom. As Tae Wan Kim illustrates, a fundamental problem is that AI is usually based on machine learning and that human biases are (explicitly or implicitly) introduced into this kind of learning. The inconsistency and the errors human beings are prone to seep into the machine learning based on computing large amounts of data. It is therefore difficult to understand Adam: 'Adam is disturbing. I have asked myself why for a year. My answer comes down to this: Seeing who I am is disturbing. [. . .] AI is mimetic—it's an imitation game. It copies us. Machines are like us.' (Kim, 2021)

The question of the nature of artificial intelligence is thus inextricably linked to the question of the nature of human intelligence and responsible action. Instead of providing answers, the novels encourage reflection on fundamental questions: What is intelligence? How can a responsible coexistence between humans and machines be created? And for how long will it, in the face of medical and technological progress, be possible to distinguish clearly between the two? After all, the genetic 'lifting' that is already part of the daily routine in Ishiguro's novel is just one of the possible ways that humans could be 'designed' in the future.

Even though one should be cautious about making predictions, particularly in academic contexts, one does not need to be a prophet to predict that, in view of the rapid development of AI alone, the themes and questions examined in this article will continue to occupy literary studies in the coming years. From the broad spectrum of current and sometimes frightening developments, I want to mention the still young field of 'digital afterlife', in which chatbots are programmed to play the role of the deceased in conversations with mourners—a precursor of what Josie's mother has planned for the event of her daughter's death. Given these developments, it

[22] Shang (2020: 447f), for example, considers Miranda's lie to be ethically justified and concludes that 'Adam fails to deal with ethical issues' because he negates human emotions.

seems likely that there will continue to be numerous novels, plays and films that use literary devices to explore the tension between different kinds of human and artificial intelligence. The research desiderata outlined at the beginning of this article will in all likelihood persist, and it is to be hoped that the connection between literature and intelligence will in future be given the attention it deserves.

References

Batson, D. C., Polycarpou, M. P., Harmon-Jones, E., Imhoff, H. J., Mitchener, E. C., Bednar, L. L., Klein, T. R., & Highberger, L. (1997). Empathy and attitudes—Can feeling for a member of a stigmatized group improve feelings toward the group? *Journal of Personality and Social Psychology, 72*(1), 105–118.

Cianciolo, A. T., & Sternberg, R. J. (2004). *Intelligence: A brief history*. Blackwell.

Corrigan, M. (2021). Klara and the sun is a masterpiece about life, love and mortality. *NPR* (3 Mar 2021). Retrieved April 29, 2021, from https://www.npr.org/2021/03/03/972841445/klaraand-the-sun-is-a-masterpiece-about-life-love-and-mortality

Costa, P., & Ribas, L. (2019). AI becomes her: Discussing gender and artificial intelligence. *Technoetic Arts, 17*(1–2), 171–193.

Csapó, B., & Funke, J. (Eds.). (2017). *The nature of problem solving. Using research to inspire 21st century learning*. OECD. https://doi.org/10.1787/9789264273955-en

Devlin, K. (2018). *Turned on: Science, sex and robots*. Bloomsbury.

Draguhn, A. (2022). On the neurobiology of intelligence. In R. Holm-Hadulla, J. Funke, & M. Wink (Eds.), *Intelligence: Theoretical foundations and pragmatic applications*. Heidelberg University Publishing.

Ellemers, N. (2018 [2017]). Gender Stereotypes. *Annual Review of Psychology, 69*(1), 275–298.

Fischer, A. H., Kret, M. E., & Broekens, J. (2018). Gender differences in emotion perception and self-reported emotional intelligence: A test of the emotion sensitivity hypothesis. *PLoS One, 13*(1), e0190712.

Georgiou, G. K., Guo, K., Naveenkumar, N., Viera, A. P. A., & Das, J. P. (2020). PASS theory of intelligence and academic achievement: A meta-analytic review. *Intelligence, 79*, 101431. https://doi.org/10.1016/j.intell.2020.101431

Giles, J. (2019). Love, sex and robots collide in a new McEwan novel. *New York Times.* Retrieved May 17, 2021, from https://www.nytimes.com/2019/05/01/books/review/ian-mcewan-machines-like-me.html

Goleman, D. (1995). *Emotional intelligence*. Bantam Books.

Green, M. C., & Brock, T. C. (2000). The role of transportation in the persuasiveness of public narratives. *Journal of Personality and Social Psychology, 79*(5), 701–721.

Green, M. C., & Dill, K. E. (2013). Engaging with stories and characters: Learning, persuasion, and transportation into narrative worlds. In K. E. Dill (Ed.), *The Oxford handbook of media psychology* (pp. 449–461). Oxford University Press.

Halpern, D. F., & LaMay, M. L. (2000). The smarter sex: A critical review of sex differences in intelligence. *Educational Psychology Review, 12*(2), 229–246.

Heise, U. (2006). The Hitchhiker's guide to ecocriticism. *PMLA, 121*(6), 503–516.

Herpertz, S. (2022). Interpersonal Intelligence. In R. Holm-Hadulla, J. Funke, & M. Wink (Eds.), *Intelligence: Theoretical foundations and pragmatic applications*. Heidelberg University.

Hester, H. (2017). Technology becomes her. *New Vistas, 3*(1), 46–50.

Hoffman, M. L. (2000). *Empathy and moral development: Implications for caring and justice*. Cambridge University Press.

Hüther, G. (2006). Wie lernen Kinder? Voraussetzungen für gelingende Bildungsprozesse aus neurobiologischer Sicht. In R. Caspary (Ed.), *Lernen und Gehirn: Der Weg zu einer neuen Pädagogik* (pp. 70–84). Herder.

Ishiguro, K. (2021). *Klara and the sun*. Faber & Faber.

Johnson, D. R., Jasper, D. M., Griffin, S., & Huffman, B. L. (2013). Reading narrative fiction reduces Arab-Muslim prejudice and offers a safe haven from intergroup anxiety. *Social Cognition, 31*(5), 578–598.

Kidd, D. C., & Castano, E. (2013). Reading literary fiction improves theory of mind. *Science, 342*(6156), 377–380.

Kim, T. W. (2021). Flawed Like Us and the Starry Moral Law: Review of Machines Like Me by Ian McEwan. *Journal of Business Ethics, 170*, 875–879. https://doi.org/10.1007/s10551-021-04758-8

Loh, J. (2019). *Robotherethik: Eine Einführung*. Suhrkamp.

Mar, R. A., Oatley, K., Hirsh, J., dela Paz, J., & Peterson, J. B. (2006). Bookworms versus nerds: Exposure to fiction versus non-fiction, divergent associations with social ability, and the simulation of fictional social worlds. *Journal of Research in Personality, 40*(5), 694–712.

Mayer, J. D., Salovey, P., & Caruso, D. R. (2000). Models of emotional intelligence. In R. J. Sternberg (Ed.), *Handbook of intelligence* (pp. 392–420). Cambridge University Press.

McEwan, I. (2019). *Machines like me and people like you*. Jonathan Cape.

Menevis, I., & Özad, B. E. (2014). Do age and gender influence multiple intelligences? *Social Behavior and Personality, 42*, 9–20.

Nickerson, R. S., Butler, S. F., & Carlin, M. (2009). Empathy and knowledge projection. In J. Decety & W. Ickes (Eds.), *The social neuroscience of empathy* (pp. 43–56). MIT Press.

Nünning, V. (2014). *Reading fictions, changing minds: The cognitive value of fiction*. Winter.

Oatley, K. (2016). Fiction: Simulation of social worlds. *Trends in Cognitive Sciences, 20*(8), 618–628.

Ricœur, P. (1984 [1983]). *Time and narrative* (Vol. 1). University of Chicago Press.

Schiffer, K., Ennemoser, M., & Schneider, W. (2002). Die Beziehung zwischen dem Fernsehkonsum und der Entwicklung von Sprach- und Lesekompetenz im Grundschulalter in Abhängigkeit von der Intelligenz. *Zeitschrift für Medienpsychologie, 14*(1), 2–13. https://doi.org/10.1026//1617-6383.14.1.2

Schildknecht, C. (2007). 'Ein seltsam wundersamer Anstrich'? Nichtpropositionale Erkenntnis und ihre Darstellungsformen. In B. Bowman (Ed.), *Darstellung und Erkenntnis: Beiträge zur Rolle nichtpropositionaler Erkenntnisformen in der deutschen Philosophie und Literatur nach Kant* (pp. 31–43). Mentis.

Schwartz, S. H. (2012). An overview of the Schwartz theory of basic values. *Online Readings in Psychology and Culture, 2*(1), 1–20.

Shang, B. (2020). From Alan Turing to Ian McEwan: Artificial intelligence, lies and ethics in machines like me. *Comparative Literature Studies, 57*(3), 443–453.

Smith, Z. (2020). Peonies. In *Intimations: Six essays* (pp. 1–11). Penguin.

Sternberg, R. J. (1998). A balance theory of wisdom. *Review of General Psychology, 2*, 347–365.

Sternberg, R. J. (2019a). A theory of adaptive intelligence and its relation to general intelligence. *Journal of Intelligence, 7*, 4. https://doi.org/10.3390/jintelligence7040023

Sternberg, R. J. (2019b). Intelligence. In R. J. Sternberg & W. Pickren (Eds.), *Handbook of the intellectual history of psychology: How psychological ideas have evolved from past to present* (pp. 267–286). Cambridge University Press.

Sternberg, R. J., & Glück, J. (2019). Wisdom, morality, and ethics. In R. J. Sternberg & J. Glück (Eds.), *Cambridge handbook of wisdom* (pp. 551–574). Cambridge University Press.

Vera Nünning is Professor of English Philology at the University of Heidelberg, where she also served as Prorector for International Relations. She was a visiting professor at the Universities of Zaragoza (2006), Lisbon (2009), Helsinki (2010) and Bergamo (2011). From 2009 to 2019, she

was Vice President of the German Consortium of the Turkish-German University in Istanbul. She has also had the good fortune to be a Fellow in different Institutes of Advanced Study. She teaches and publishes in the fields of British literature as well as culture, with a focus on cultural theory, narrative theory, and British literature since the eighteenth century. She is (co-)author of 11 monographs and (co-)editor of 25 volumes as well as three book series and the journal *English Studies*.

Part VII
Political Intelligence and Wisdom

Chapter 20
Meta-Intelligence: Understanding, Control, and Coordination of Higher Cognitive Processes

Robert J. Sternberg

Abstract Higher cognitive processes are often characterized as fitting into categories that, while treated as natural kinds, actually are human-made inventions, such as intelligence, creativity, and wisdom. Other germane categories include reasoning, problem solving, and concept formation. The different categories generate their own journals, their own tests, their own training programs, and, of course, their own cadres of researchers who specialize in one (or, more rarely, more than one) of the categories. I suggest in this chapter that the mental structures and processes underlying these various categories are largely the same. For example, all of them require meta-components, or executive processes, such as recognizing the existence of problems, defining the nature of problems, formulating strategies to solve problems, and so forth. Their utilization also requires certain attitudes. What differs is the purpose to which processes and attitudes are utilized. In intelligence, the processes and attitudes are used primarily for knowledge acquisition, utilization, and analysis. In creativity, the processes and attitudes are used to generate new, useful ideas. In wisdom, the processes and attitudes are used to seek a common good. The arbitrariness of these separate categories serves artificially to isolate related theoretical and empirical work that should integrate intelligence, creativity, and wisdom. In this article, I discuss how the construct of meta-intelligence helps bring unity to theory and research endeavors that are now viewed as being largely independent of each other.

1 Introduction

Theory and research on higher cognitive processes are divided into a number of largely discrete categories. In approaches that had their origins in differential psychology, major categories have been intelligence, creativity, and wisdom. In

R. J. Sternberg (✉)
Department of Psychology, College of Human Ecology, Cornell University, Ithaca, NY, USA
e-mail: robert.sternberg@cornell.edu; https://www.robertjsternberg.com

R. M. Holm-Hadulla et al. (eds.), *Intelligence - Theories and Applications*,
https://doi.org/10.1007/978-3-031-04198-3_20

approaches that had their origins in cognitive-experimental psychology, categories have been ones such as problem solving, reasoning, concept formation, and the like. These different categories have been perceived as different, although partially overlapping domains of psychological inquiry. They have given rise to different fields of endeavor, with largely different researchers, journals, professional societies, and graduate programs to prepare the next generation of researchers.

Worth considering is that these categories are human constructions or stipulated concepts. They are artificially constructed because they are convenient. For example, a textbook on The Psychology of Human Thought (Sternberg & Funke, 2019), has separate chapters for intelligence (Wilhelm & Schroeders, 2019), creativity (Lubart & Thornhill-Miller, 2019), wisdom (Glück, 2019), problem solving (Funke, 2019), reasoning (Davidson, 2019; Evans, 2019), decision-making (Nolte et al., 2019), and concepts (Levering & Kurtz, 2019), as have other similar books in the past (Sternberg & Ben-Zeev, 2001; Sternberg & Smith, 1988). Other books have related topics (e.g., Minda, 2020).

2 Relations Among Intelligence, Creativity, Wisdom, and Related Constructs

Clearly, the categories are highly overlapping. For example, in the differential-psychological domain, a typical divergent-thinking task used to measure creativity ("What are unusual uses of a paperclip?") requires divergent thinking, but also requires analytically intelligent thinking to determine whether a given answer produced by divergent thinking is appropriate. As an example, the paperclip might be used to tie up a plastic garbage bag; but if one generates the answer that it can be used as a substitute for toilet paper, that's harder to imagine! One needs an analytical filtering mechanism to screen out bad creative ideas. Similarly, wise decisions, such as how to contain a burgeoning pandemic, require both creative thinking—something that has been somewhat hard to find during the COVID-19 pandemic—and analytical thinking to ensure that novel ideas—such as drinking bleach to purify one's insides—are removed if they are not useful or even are harmful.

In the cognitive-experimental domain, "reasoning" requires solving inductive- or deductive-reasoning problems, so clearly, people who reason are solving problems. They also have to decide what answer is correct, so the problems involve decision making. In a typical inductive-reasoning problem, reasoners have to learn one or more concepts, such as that a number series has the pattern "+2, −3," as in "8, 10, 7, 9, 6, …?" so concept-learning is involved as well.

The different domains are clearly related, and yet insularity can make it difficult to conduct and publish research that cross-cuts categories. For example, if one develops a theory that cross-cuts intelligence, creativity, and wisdom, one may be at a loss as to where to submit an article based on the theory, at least if one wishes to submit it to a somewhat specialized journal. The problem is that intelligence and creativity journals are distinct and there currently are no wisdom journals at all.

The disadvantage to this modular approach is that the modules are not really modules. Claiming to have modules when one does not have modules is probably a bad idea because it creates illusory separations. The concepts of intelligence, creativity, and wisdom all overlap. For example, we know that explicit psychometric measures of intelligence, creativity, and wisdom are all intercorrelated (Lynch & Kaufman, 2019; Staudinger et al., 1997), as are implicit-theory based measures (Sternberg, 1985b). Conceptually, the three are difficult cleanly to distinguish (Sternberg, 2003b); one theory, a balance theory of wisdom, views wisdom as inevitably involving creativity and intelligence (Sternberg, 2019b).

Creativity and intelligence always have been very closely related conceptually (Sternberg & O'Hara, 2000). Guilford (1967) viewed creativity as largely a subset of intelligence, with divergent thinking one of the operations in his theory that could be applied to various contents and products. Gardner (2011a) has analyzed the creativity of famous creators in terms of his theory of multiple intelligences (Gardner, 2011b). A recent theory views successful intelligence, a broad construct, as drawing on analytical intelligence, creative intelligence, and wisdom (Sternberg, 2020a). CHC (Cattell-Horn-Carroll) theory places creativity in long-term storage and retrieval (Glr), and fluid intelligence is also related to creativity (Carroll, 1993; Cattell, 1971; McGrew, 2005).

The differentiations in the cognitive literature among reasoning, problem solving, decision making, and concept formation are even harder to make. Reasoning problems are, well, problems. There is a problem to be solved. Decisions need to be made about the correct answer. Decision making usually requires solving some kind of problem, such as whether to do one thing or another. And concept formation is required for solving any kind of problem for one to learn enough information to be able to solve the kind of problem (see Sternberg & Funke, 2019).

In the augmented theory of successful intelligence (Sternberg, 2020a), creative intelligence—which is the ability part of creativity—is used to generate new ideas; analytical intelligence is used to ascertain the quality of those ideas; practical intelligence is used to put the ideas into practice and convince others of the value of the ideas; and wisdom is used to ensure that the ideas are used to help promote a common good. According to this theory, the cognitive processes used for the different aspects of intelligence are all largely the same, namely a set of meta-components, or executive processes—processes that were introduced in a much earlier version of the theory (Sternberg, 1980, 1983).

The meta-componential processes apply to all problem solving of any kind, including (a) recognition of the existence of a problem; (b) definition of the problem; (c) mental representation of the problem; (d) allocation of resources to the problem; (e) formation of a strategy for solving the problem; (f) monitoring of problem solving as it is ongoing; (g) evaluation of the solution to the problem after it is solved (see Funke, 2019, for a more comprehensive overview of processes of problem solving). On this view, all problems—whether seemingly based on intelligence, creativity, wisdom, or some combination; or whether requiring problem solving, reasoning, decision making, concept formation, or some combination—require execution of some and probably all of these meta-components.

This enumeration comprises a fairly standard list of executive processes (see also, e.g., Bransford & Stein, 1993; Brown, 1978; Feuerstein, 1979, 1980). To my knowledge, the executive meta-componential processes, unlike performance components that execute the instructions of meta-components, have not been experimentally separated (see Sternberg, 1983, 1985a).

For example, suppose the problem is a fluid-intelligence problem, such as an analogy. There are some necessary steps, which may or may not be conscious. One has to recognize that there is a problem. Then one has to define it as an analogy. Next one has to decide how to represent the information in the problem—in terms of features, a spatial representation, or whatever. Then one needs to decide how to allocate mental resources, as well as time, to solve the problem, and to set up a strategy to solve the problem. One then has to monitor one's problem solving and evaluate it after one is done.

Test-like analogy problems are, arguably, somewhat trivial, although Spearman (1923, 1927) saw analogies as a primary basis for intelligent thinking. Consider now more complex problem.

For intelligence, consider comparing and contrasting two vaccines for their efficacy, safety, cost, portability, storage requirements, and the like. The executive processes would be the same as for the analogy. One would have to recognize there is a problem—a disease in need of a vaccine. One would have to define the problem—choosing which of two vaccines is a better choice. One would have to allocate resources to making a decision. One would have to represent the problem, set up a strategy to solve the problem, and then monitor and evaluate one's solution.

Consider now a creativity problem. Suppose one is designing the next year's model of a car. This year the car has not sold well. You want to design a new model that will sell better than the old model. You have to be creative, because what the car company is doing now is not working. So, you need to recognize there is a problem—the car is not selling well. You have to define the problem—why is the car not selling well? Is it the engineering, the design, the marketing, the sales force, the repair record, or what? If it is the design, what is wrong with the design? You then need to represent the problem—what does the current car look like and what does it need to look like? Maybe you will draw schematics of old and new versions. You need to decide how much time to allocate to the project and how you can stay within the budget allocated for the project. You need to create a strategy for designing and engineering the product—how are you actually going to make it happen? As you put the new car into production, you have to monitor whether the new version actually does fix what was wrong with the old version without introducing new problems. Finally, when a prototype is produced, you have to evaluate whether it actually works.

Finally, consider a wisdom-based problem. Two countries, X and Y, are drawing on a common water source. Country X accuses the other country, Y, of taking more than its allotted share of the water. (This is actually happening today with the United States and Mexico.) Relations are deteriorating quickly over the conflict regarding the water source. And water is getting scarcer all around. How do the two countries resolve their dispute? They recognize there is a problem. They are seriously at odds with each other. They define the problem as either X's stealing more than its allotted share of water, or of Y's believing that X is stealing more than its fair share of water, even though it's not, or of X and Y disagreeing as to what fair shares of water are. They need to represent the problem, so perhaps they create a schematic of the shared water source, and the water flow to each of the countries. They need to decide how much time, money, and person-power to devote to solving the problem. They need to set up a strategy to solve the problem, perhaps appointing some kind of joint commission. They need to monitor the progress of the commission and then evaluate, at the end, whether the commission did indeed reach a solution acceptable to both countries.

The same meta-components can be applied to all three types of problems. How, then, do the problems differ? They differ in what they are trying to accomplish—in their desired end-state. The intelligence problem with the vaccines is largely analytical and convergent—compare two vaccines on the basis of available information and decide which is a better choice. The creativity problem is largely one of discovery and invention. It is divergent—create a new model for a car that has not been selling. The wisdom-based problem is one of finding a common good.

On this view, what differs among intelligence, creativity, and wisdom is not the underlying mental processes, mental representations, or even need to formulate strategies and strategic goals. Rather the difference is one of purpose in problem solving. What is the problem solver trying to accomplish?

In point of fact, the three problems, like all problems, are not pure. There are few if any "pure" intelligence, creativity, or wisdom problems. The creativity problem, for example, requires at least some consideration of a common good. One wants purchasers to be happy with their purchase, stockholders to be happy with their profits, management to be happy with the enhancement of their product line, workers to be happy with their chance to develop something new, etc. The intelligence problem requires one to choose a vaccine that will help to achieve a common good for vaccine users, and it does require creativity in deciding the bases one should use for comparing the vaccines.

On the current view, use of intelligence, creativity, and wisdom involves not only mental processes but also attitudes. One has to want to use the processes, or they never will get used. The biggest stumbling block to the use of creativity, for example, is not lack of creative skills, but rather attitudinal—the fear of using creativity because its use will engender opposition (Sternberg, 2018; Sternberg & Lubart, 1995). Wisdom also can and often does engender opposition, as Socrates learned in ancient times, paying for his wisdom with his execution. But the same problem exists today: as Malala Yousafzai discovered when she was shot for advocating the rights of young women to an education in Pakistan. Sometimes, even the use of intelligence can engender opposition, as leaders discover who are smarter than their followers and therefore are mocked for being too bookish (Sternberg, 2003a). To some extent, this happened in the United States to Harvard-educated Barack Obama, who spoke and wrote at a level higher than that of many of his constituents.

3 The Nature of Meta-Intelligence

Put another way, many serious life problems require some of intelligence, creativity, and wisdom jointly. The greatest problem is where, when, and how to allocate them—and this is the problem that the higher order construct of meta-intelligence is intended to solve. *Meta-intelligence* is understanding, control, and coordination of higher cognitive processes, such as the processes of intelligence, creativity, and wisdom, or problem solving, reasoning, decision making, and concept formation. Just as there are three levels of abilities in Carroll's (1993) three-tier model of human intelligence, here there are four levels of functioning, as shown in Fig. 20.1.

In particular, meta-intelligence is at the top level of the hierarchy. It provides understanding, control, and coordination of the various aspects of intellectual functioning. When taken from a differential-psychological standpoint, these aspects include intelligence, creativity, and wisdom. When taken from a cognitive-experimental standpoint, these aspects include problem solving, reasoning, decision making, and concept formation. These aspects of functioning are highly overlapping, both between methodological categories (differential and cognitive-experimental) and within methodological categories (intelligence, creativity, wisdom; or reasoning, problem solving, decision making, concept formation).

These aspects of functioning are, in turn, a result of meta-componential thinking, otherwise known an executive processing. The meta-components, in turn, control the utilization of performance components, which solve problems, and of knowledge-acquisition components, which learn how to solve the problems in the first place (Sternberg, 1983).

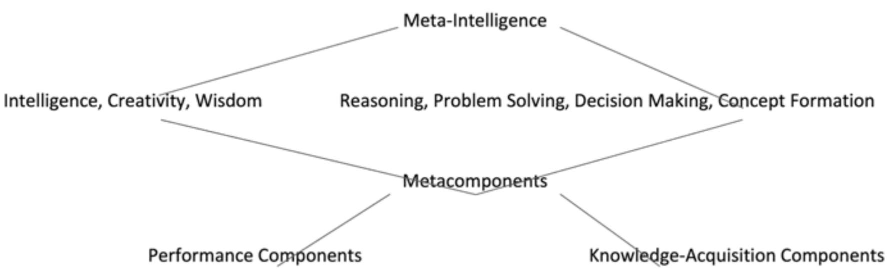

Fig. 20.1 Levels of higher cognitive processes. Meta-intelligence, at the top level, provides understanding, control, and coordination of aspects of intellectual functioning. From a differential-psychological standpoint, these aspects are intelligence, creativity, and wisdom. From a cognitive-experimental standpoint, these aspects are reasoning, problem solving, decision making, and concept formation. These aspects are highly overlapping, both between categories (differential and cognitive-experimental) and within categories (intelligence, creativity, wisdom; or reasoning, problem solving, decision making, concept formation). These aspects are in turn a function of meta-componential thinking, otherwise known an executive processing. The meta-components in turn control performance components, which solve problems, and knowledge-acquisition components, which learn how to solve the problems in the first place. (Source: own illustration)

One might argue, of course, that meta-intelligence is just another manifestation of g. However, the correlational patterns across intelligence, creativity, and wisdom simply do not support such an interpretation. Although there are correlations, they are modest. And at the level of construct-validation, it is quite clear that intelligence tests, from which the g factor is extracted, do not well measure either creativity or wisdom. On the contrary, there are many intelligent people who are not particularly creative or wise.

Rather, meta-intelligence serves a coordinating and control function over the different processes of higher of higher order cognition as they serve different purposes, either to analyze and solve, or learn how to solve problems in the first place (intelligence); to create new problems or solutions (creativity); or to solve problems in a way that promotes a common good rather than just one's own (wisdom). What differs is not the set of processes, but rather the purposes to which they are put.

Does the construct of meta-intelligence exist? Well, in the sense that there must be coordination among the functions of intellectual functioning as they serve different purposes, it must exist at some level. Is it a single entity? We do not know. But we do not know whether g is a single entity either. Rather, g is a statistical regularity derived from scores on intelligence tests. One could conceive of a meta-intelligence test, which would present problems and require one to decide when and how to use the different cognitive functions, whether intelligence, creativity, or wisdom in the differential-psychological tradition, or problem solving, reasoning, decision making, or concept formation in the cognitive-experimental tradition.

Does a construct of meta-intelligence serve a useful purpose? The construct is new, so only time will tell. It will need to be construct-validated. But I believe it serves at least three important purposes.

First, meta-intelligence is the means by which we understand our own range of higher mental abilities. What are the various things we can do with our minds? The various "things" are not abilities, like verbal, quantitative, and spatial, for example, but rather, organized collections of these abilities that can serve different purposes—intelligence, creativity, and wisdom, for instance. We understand that we can recognize, define, and solve convergent problems (intelligence), divergent problems (creativity), and problems with solutions seeking a common good (wisdom).

Second, meta-intelligence is the means by which we control which set of collections of abilities we use when and how. Creativity is useful in many instances, but likely not when solving a multiple-choice standardized test problem. Intelligence is useful, but sometimes, maximizing one's own individual outcomes, as in optimizing one's career success, can come at the expense of the greater common good, as, for example, when one's career success results in making other people's lives worse (such as those careers that contribute ultimately to harming people, such as through air or water pollution).

Third and finally, meta-intelligence coordinates the use of the different collections of abilities. A given problem may require intelligence, creativity, and wisdom, such as a problem of how to allocate scarce resources, such as of a new vaccine against an illness that has become a pandemic. Meta-intelligence enables us to know what to do when.

Some researchers might, understandably, be reluctant to introduce yet another construct to those already in the list of psychological constructs currently being used. But I would suggest that we have always utilized a construct functionally equivalent to meta-intelligence, without giving it a name. We've always known that people need to decide what kinds of higher order mental resources they need to allocate to a given problem. Meta-intelligence simply names this construct.

A similar construct, of course, is metacognition (see, e.g., Fiedler et al., 2019). Metacognition involves understanding, control, and coordination of cognitive processes. Meta-intelligence is different, however, because it involves attitudes, as described above, not just cognitive processes. Utilization of intelligence, creativity, and wisdom, as well as of various functions of problem solving, reasoning, and decision making, can involve attitudes as much as it involves cognitive processes. As noted above, failures of utilization are at least as likely to be attitude-based as process-based. A person decides not to be creative not because they can't be, but because they fear the consequences, and often, rightfully so (Sternberg, 2020b).

Another similar construct is self-regulation (Vohs & Baumeister, 2017). Whereas metacognition is narrower than meta-intelligence, self-regulation is much broader, applying as it does to all aspects of a person, whether related to intellectual, emotional, or motivational functions. Self-regulation falls much more broadly into the domains of personality, social, and clinical psychology as well as of cognitive psychology.

A reaer of this essay may wonder whether the appropriate construct would be some new kind of "meta-cognition" rather than "meta-intelligence"—the combination, of intelligence, creativity, and wisdom. There might be some value in such a construct, but that construct, if it exists, is not what this essay is about. Rather, this essay is about knowing what skills and attitudes to utilize where and when—under what circumstances. It is not some unified power, but rather, a power to understand, control, and coordinate different functions of the mind.

Other researchers might want to know where in the brain meta-intelligence is located. I doubt it is located in any one place, any more than intelligence is (Haier, 2020; Haier & Jung, 2007; Jung & Haier, 2007). Gardner (2011b) might disagree, but the current evidence is for broad distribution of intellectual skills in the brain. Almost certainly, meta-intelligence is distributed across parts of the brain. But the exact parts remain to be determined. It further remains to be determined whether meta-intelligence can be extracted as a (probably higher order) psychometric factor. This is a first paper on the construct, and so many questions remain to be answered.[1]

Is there any urgency to introducing such a construct? I believe there is. What has become clear, perhaps depressingly clear, is that the serious problems facing the world today cannot, or at best, have not been successfully solved by general

[1] Although written subsequent to the writing of this paper, a follow-up paper was actually published first (i.e., earlier during calendar year 2021): Sternberg, R. J., Glaveanu, V., Karami, S., Kaufman, J. C., Phillipson, S. N., & Preiss, D. D. (2021). Meta-intelligence: Understanding, control, and interactivity between creative, analytical, practical, and wisdom-based approaches in problem solving. *Journal of Intelligence, 9*, 19, https://doi.org/10.3390/jintelligence9020019

intelligence alone (Sternberg, 2019a, b, 2021). They take some kind of coordination of analytical-intelligence skills with creative and wisdom-based ones as well. That coordination so far has been lacking. Global climate change, air pollution, water pollution, weapons of mass destruction, and pandemics, require creative and wise solutions that general intelligence alone does not provide. Meta-intelligence provides the key to coordinating these mental resources. We just have to find it within ourselves, utilize it, and develop it within our young people in order to reach better solutions to world problems than we so far have generated.

There is a tendency in intelligence research, and in some creativity and wisdom research, to turn inward—to seek more and more refined understanding of cognitive and biological processes involved in intellectual functioning. Broader problems may be seen as beyond our range—as philosophical or political. But the construct we are studying, at least of intelligence, is too narrow. The world cannot afford a lot more high-g (general-intelligence) people that allow the conditions under which we live to keep becoming more and more degraded. Eventually, we may find IQs have gone higher and higher (Flynn, 2012), while adaptivity to the world has been left to viruses, bacteria, and cockroaches. That is not the future we want to look forward to. Meta-intelligence may provide one start toward understanding intelligence, creativity, and wisdom in their broader and interactive contexts within the world.

References

Bransford, J. D., & Stein, B. S. (1993). *The ideal problem solver: A guide for improving thinking, learning, and creativity* (2nd ed.). Freeman.

Brown, A. L. (1978). Knowing when, where, and how to remember: A problem of metacognition. In R. Glaser (Ed.), *Advances in instructional psychology* (Vol. 1, pp. 77–165). Erlbaum.

Carroll, J. B. (1993). *Human cognitive abilities: A survey of factor-analytic studies*. Cambridge University Press.

Cattell, R. B. (1971). *Abilities: Their structure, growth, and action*. Houghton-Mifflin.

Davidson, J. E. (2019). Inductive reasoning. In R. J. Sternberg & J. Funke (Eds.), *The psychology of human thought* (pp. 133–154). Heidelberg University. Retrieved from https://books.ub.uni-heidelberg.de/index.php/heiup/catalog/book/470

Evans, J. B. T. (2019). Deductive reasoning. In R. J. Sternberg & J. Funke (Eds.), *The psychology of human thought* (pp. 113–132). Heidelberg University. Retrieved from https://books.ub.uni-heidelberg.de/index.php/heiup/catalog/book/470

Feuerstein, R. (1979). *The dynamic assessment of retarded performers: The learning potential assessment device, theory, instruments, and techniques*. University Park Press.

Feuerstein, R. (1980). *Instrumental enrichment: An intervention program for cognitive modifiability*. University Park Press.

Fiedler, K., Ackerman, R., & Scarampi, C. (2019). Metacognition: Monitoring one's own knowledge, reasoning and decisions. In R. J. Sternberg & J. Funke (Eds.), *The psychology of human thought: An introduction* (pp. 89–110). Heidelberg University. Retrieved from https://books.ub.uni-heidelberg.de/index.php/heiup/catalog/book/470

Flynn, R. J. (2012). *Are we getting smarter?* Cambridge University Press.

Funke, J. (2019). Problem solving. In R. J. Sternberg & J. Funke (Eds.), *The psychology of human thought: An introduction* (pp. 155–176). Heidelberg University. Retrieved from https://books.ub.uni-heidelberg.de/index.php/heiup/catalog/book/470

Gardner, H. (2011a). *Creating minds*. Basic Books.
Gardner, H. (2011b). *Frames of mind: The theory of multiple intelligences* (Revised ed.). Basic Books.
Glück, J. (2019). Wisdom. In R. J. Sternberg & J. Funke (Eds.), *The psychology of human thought: An introduction* (pp. 307–326). Heidelberg University. Retrieved from https://books.ub.uni-heidelberg.de/index.php/heiup/catalog/book/470
Guilford, J. P. (1967). *The nature of human intelligence*. McGraw-Hill.
Haier, R. J. (2020). Biological approaches to intelligence. In R. J. Sternberg (Ed.), *Human intelligence: An introduction* (pp. 139–173). Cambridge University Press.
Haier, R. J., & Jung, R. E. (2007). Beautiful minds (i.e., brains) and the neural basis of intelligence. *Behavioral and Brain Sciences, 30*(2), 174–178.
Jung, R. E., & Haier, R. J. (2007). The parieto-frontal integration theory (P-FIT) of intelligence: Converging neuroimaging evidence. *Behavioral and Brain Sciences, 30*(2), 135–154.
Levering, K. R., & Kurtz, K. J. (2019). Concepts: Structure and acquisition. In R. J. Sternberg & J. Funke (Eds.), *The psychology of human thought: An introduction* (pp. 55–70). Heidelberg University. Retrieved from https://books.ub.uni-heidelberg.de/index.php/heiup/catalog/book/470
Lubart, T. I., & Thornhill-Miller, B. (2019). Creativity: An overview of the 7C's of creative thought. In R. J. Sternberg & J. Funke (Eds.), *The psychology of human thought: An introduction* (pp. 277–306). Heidelberg University. Retrieved from https://books.ub.uniheidelberg.de/index.php/heiup/catalog/book/470
Lynch, S. F., & Kaufman, J. C. (2019). Creativity, intelligence, and wisdom: Could versus should. In R. J. Sternberg & J. Glück (Eds.), *Cambridge handbook of wisdom* (pp. 455–464). Cambridge University Press.
McGrew, K. S. (2005). The Cattell-Horn-Carroll theory of cognitive abilities: Past, present, and future. In D. P. Flanagan & P. L. Harrison (Eds.), *Contemporary intellectual assessment: Theories, tests, issues* (2nd ed., pp. 136–181). Guilford Press.
Minda, J. P. (2020). *The psychology of thinking: Reasoning, decision-making, and problem solving* (2nd ed.). Sage.
Nolte, J., Garabito, D., & Reyna, V. (2019). Decision making. In R. J. Sternberg & J. Funke (Eds.), *The psychology of human thought: An introduction* (pp. 177–198). Heidelberg University. Retrieved from https://books.ub.uni-heidelberg.de/index.php/heiup/catalog/book/470
Spearman, C. (1923). *The nature of intelligence and the principles of cognition*. Macmillan.
Spearman, C. (1927). *The abilities of man*. Macmillan.
Staudinger, U. M., Lopez, D. F., & Baltes, P. B. (1997). The psychometric location of wisdom-related performance. *Personality and Social Psychology Bulletin, 23*, 1200–1214.
Sternberg, R. J. (1980). Sketch of a componential subtheory of human intelligence. *Behavioral and Brain Sciences, 3*, 573–584.
Sternberg, R. J. (1983). Components of human intelligence. *Cognition, 15*, 1–48.
Sternberg, R. J. (1985a). *Beyond IQ: A triarchic theory of human intelligence*. Cambridge University Press.
Sternberg, R. J. (1985b). Implicit theories of intelligence, creativity, and wisdom. *Journal of Personality and Social Psychology, 49*(3), 607–627.
Sternberg, R. J. (2003a). WICS: A model for leadership in organizations. *Academy of Management Learning & Education, 2*, 386–401.
Sternberg, R. J. (2003b). *Wisdom, intelligence, and creativity synthesized*. Cambridge University Press.
Sternberg, R. J. (2018). A triangular theory of creativity. *Psychology of Aesthetics, Creativity, and the Arts, 12*, 50–67.
Sternberg, R. J. (2019a). A theory of adaptive intelligence and its relation to general intelligence. *Journal of Intelligence, 7*, 23. https://doi.org/10.3390/jintelligence7040023

Sternberg, R. J. (2019b). Why people often prefer wise guys to guys who are wise: An augmented balance theory of the production and reception of wisdom. In R. J. Sternberg & J. Glück (Eds.), *Cambridge handbook of wisdom* (pp. 162–181). Cambridge University Press.

Sternberg, R. J. (2020a). The augmented theory of successful intelligence. In R. J. Sternberg (Ed.), *Cambridge handbook of intelligence* (Vol. 2, 2nd ed., pp. 679–708). Cambridge University Press.

Sternberg, R. J. (2020b, November 19). Was your idea too creative? *Inside Higher Ed*, Retrieved from https://www.insidehighered.com/advice/2020/11/19/how-avoid-having-your-ideas-rejected-being-too-creative-opinion

Sternberg, R. J. (2021). *Adaptive intelligence: Surviving and thriving in a world of uncertainty*. Cambridge University Press.

Sternberg, R. J., & Ben-Zeev, T. (2001). *Complex cognition: The psychology of human thought*. Oxford University Press.

Sternberg, R. J., & Funke, J. (Eds.). (2019). *The psychology of human thought: An introduction*. Heidelberg University Press. Retrieved from https://books.ub.uni-heidelberg.de/index.php/heiup/catalog/book/470

Sternberg, R. J., & Lubart, T. I. (1995). *Defying the crowd: Cultivating creativity in a culture of conformity*. Free Press.

Sternberg, R. J., & O'Hara, L. A. (2000). Intelligence and creativity. In R. J. Sternberg (Ed.), *Handbook of intelligence* (pp. 609–628). University Press.

Sternberg, R. J., & Smith, E. E. (1988). *The psychology of human thought*. Cambridge University Press.

Vohs, K. D., & Baumeister, R. F. (Eds.). (2017). *Handbook of self-regulation* (3rd ed.). Guilford Press.

Wilhelm, O., & Schroeders, U. (2019). Intelligence. In R. J. Sternberg & J. Funke (Eds.), *The psychology of human thought: An introduction* (pp. 255–276). Heidelberg University Press. Retrieved from https://books.ub.uni-heidelberg.de/index.php/heiup/catalog/book/470

Robert J. Sternberg is Professor of Psychology at Cornell University and Honorary Professor of Psychology at Heidelberg University. Previously, he was IBM Professor of Psychology and Education at Yale University. His PhD is from Stanford and he holds 13 honorary doctorates. Sternberg has won the Grawemeyer Award in Psychology and the James and Cattell Awards from the Association for Psychological Science. He is past-president of the American Psychological Association and the Federation of Associations in Brain and Behavioral Sciences. Sternberg's most recent books are *The Nature of Intelligence and Its Development in Childhood* (Cambridge University Press, 2020) and *Adaptive Intelligence: Surviving and Thriving in a World of Uncertainty* (Cambridge University Press, February 2021). According to Google Scholar, he has been cited roughly 210,000 times and has an h index of 222.

Chapter 21
Intelligentia Dei: Artificial Intelligence, Human Reason and Divine Wisdom

Manfred Oeming

Abstract The study analyses the significance of religious language in avant-garde technological contexts. It turns out that even the top researchers in the field of artificial intelligence (AI) are very fond of resorting to theological terminology in order to explicate the outstanding importance of their achievements. They define 'God as the most intelligent being imaginable' and identify this with the high-performance computers currently being developed. AI thus acquires the character of a salvation event and becomes the final evolutionary step of true religion. The promise of divine intelligence functions—where will be shown in a second part—in contemporary advertising as a lure for mind-expanding techniques and psychotropic drugs. In contrast, biblical literature is very sober and realistic. As the third part shows, the Old Testament wisdom, with all its appreciation of human reason, critically clarifies its limits and functions as a warning against frivolous promises of salvation by AI and a hubris of humans that threatens to lose sight of the difference of human and the divine.

1 Introduction

A chapter on 'divine intelligence', even by an Old Testament scholar dealing with religious ideas that are far more than 2000 years old—is this not completely out of line with the studies on artificial intelligence (AI) gathered in this volume, which concern quite modern issues and look ahead to the future of the twenty-first century AD? As we shall see, yes and no. It turns out, in fact, that researchers in the field of AI make astonishingly frequent recourse to religious language, and in some cases even make religious claims. First of all, therefore, under 1. we shall reflect on the *performance of ancient mythical language* in the context of natural science and intelligence technology today. In doing so, it will become clear that working with myth is meaningful, if not even necessary, even in modern times, but at the same

M. Oeming (✉)
Old Testament Theology, Theological Seminary, University of Heidelberg, Heidelberg, Germany
e-mail: Manfred.Oeming@ts.uni-heidelberg.de; https://www.uni-heidelberg.de/fakultaeten/theologie/personen/oeming.html

R. M. Holm-Hadulla et al. (eds.), *Intelligence - Theories and Applications*,
https://doi.org/10.1007/978-3-031-04198-3_21

time also harbours dangers. Under 2. it shall be unfolded that ‘divine intelligence’ in the present is often traded as a *promised good,* which is even offensively put into the shop window of advertising: mankind shall finally attain divine intelligence, he shall become like God. Divine intelligence is a recognized goal to which the top minds in business, but also in the development of artificial intelligence, aspire. Finally, under 3. it will be shown which *functions the ancient biblical traditions of God’s intelligence originally had and how the wisdom of God then (and hopefully also in the future) meets as a critical instance towards a hubris of mankind forgetting and suppressing its limits and calls mankind to its responsibility.*

2 On the Power of Religious Language in the Context of Modern Natural Sciences: Intelligibility That Springs from Myth

As soon as natural science is to be unfolded from the world of abstract formulas into the sphere of common sense, in ‘normal’ language, it needs linguistic means. In order to make its insights comprehensible beyond mathematical algorithms, it must resort to tools. It quickly becomes apparent that in the field of brain and intelligence research, too, such linguistic images derived from cultural studies become necessary. The more complex and the more obscure the theories are, the more language patterns from the world of religions suggest themselves. I once examined this in the context of the celebrations for the 100th anniversary of Robert Koch’s death: The great bacteriologist made extensive use of the language of the Old Testament’s Enemy Psalms in publishing and establishing his medical theories.[1] A tiny bacterium, whose sheer existence was still doubted by other scientists at the time, is frequently personified in Koch’s work, i.e. portrayed as a personal being capable of action and mobile, with anthropomorphic features. Just as ‘the enemies’ act in the Old Testament prayers, so too does the invisible bacterium attack: it surrounds its victims on all sides and penetrates them, it gets into position, settles down, and strikes stealthily and unexpectedly but extremely brutally from ambush. In Koch’s language, the infectious diseases are like intelligent antagonists; they prowl around looking for whom they can grab; they make use of very flexible diabolical tactics and effective responses to all defensive attempts. In the mythic prayers, this sinister ‘invasion of the enemy’ can only be stopped by God himself. Accordingly, in Koch, his vaccine had properties like God; the vaccine[2] saved from the insidious evil.

[1] Cf. Manfred Oeming, Die Mikroorganismen und die Kirche—Krankheit und Heilung bei Robert Koch, in der Stammzellenforschung und in der Bibel. In: Karlheinz Sonntag (ed.), Viren und andere Mikroben: Heil oder Plage. Zum 100. Todestag von Robert Koch, Heidelberg: Winter 2011, 145–173; in this article I was able to build on the following Germanistic research: Marianne Hänseler, Metaphern unter dem Mikroskop. Die epistemische Rolle von Metaphorik in den Wissenschaften und in Robert Kochs Bakteriologie (Legierungen 6), Zurich: Chronos 2009.

[2] As a drug, he tested the arsenic-containing drug Atoxyl on humans.

At the beginning of the twentieth century it was about the African sleeping sickness, which caused the German colonial soldiers as well as the armies of native aid workers to fall ill en masse. (By the way, the Nobel Prize winner Koch did human experiments in Africa in 1905/6, which were forbidden in Germany, and falsified the results concerning the efficacy of his preparation in order to secure research funds for his institute from the German army (Deutsches Heer). In fact, he simply concealed the fact that after his initial successes, sleeping sickness returned—within a few weeks—and claimed a very large number of lives). In Koch's work, the vaccine is cloaked in the role of the saving god who strikes down the sinister and insidious enemy. This is not different in the current depiction of vaccines against Covid-19. Religious metaphors can thus be harnessed to illustrate scientific insights.

One also encounters such theological 'language games' in the field of current intelligence research. There are surprisingly many and also surprisingly prominent personalities who productively engage in these religious, quasi-theological spheres of thought. The transition from the study of intelligence into the sphere of the religious seems almost seductive. Only the connection with the aura of the divine expresses what intelligence researchers ultimately think of themselves. We will be like God, nay, we will generate God. Let us take four brief examples:

Ray Kurzweil (born in 1948), who is very important in the history of *google,* has developed a theory for the reduction of complexities[3]: He assumes that the brain is hierarchically ordered; the structure of the world is reflected in this structure: the hierarchy of being is reflected in the existence of the approximately 300 million pattern recognizers in the human neocortex. The human brain merely uses *an* algorithm for its pattern recognition processes. As a result, the technical creation of a *model of* a human brain becomes possible. With the production of this artificial intelligence on a par with humans, which Kurzweil predicts for the year 2029, a new era will begin: the '*age of conscious machines*'. These technical products would be able to perform feats that until now could only be attributed to humans. But not only that: these conscious machines will be able to produce new, even more intelligent machines. This creation of artificial intelligence by artificial intelligence leads to another epochal leap: in 2045, humans would visibly merge with the artificial intelligence they have created. Humans would then transcend the cumbersome limitations previously imposed on them by their biological bodies. This is a new way of being: human, machine and databases will merge into a form of '*posthuman cyborg*'. 'With the development of psychological science about a century ago, so-called psycho-utopian visions of a better society arose, based on the transformation of the human mind. Such visions seem today to have been replaced by digital utopias, based on the development of superfast computers and the enhancement of brain capacity through neural implants. The latter is a prominent feature of so-called transhumanism.'[4] Here the myth of the creation of man by God is clearly taken up

[3] Ray Kurzweil, How to Create a Mind: The Secret of Human Thought Revealed, New York: Viking Books 2012 (Herman translation: Das Geheimnis des menschlichen Denkens. Einblicke in das Reverse Engineering des Gehirns, Berlin: Lola Books 2014).

[4] Bo Dahlin, The transhumanist ideas of Ray Kurzweil, Futures, 44 (2012), pp. 55–63, 55.

and perpetuated: 'Our posthuman futures and education: Homo Zappiens, Cyborgs, and the New Adam', is Bo Dahlin's appropriate title.[5]

Google's founders *Lawrence Edward Page* (born in 1973) and *Sergey Brin* (also born in 1973) go even further; they have seriously set themselves the goal of overcoming death. It's hard to believe, but these arguably undeniably highly intelligent engineers founded Calico in 2013 a company that aims to decipher the biology of aging and thereby incrementally extend life. This was followed in 2015 by Verily, a company designed to anticipate and thereby cure disease. If cancer could be defeated, people could live an average of three years longer. But that is still not enough for them: real progress would only be achieved when death was defeated. With these visions, classical religious hopes of the Old and New Testament are taken up and given as the goal of the development of AI: 'He swallows up death forever, and the Lord Yahweh will wipe away tears from every face' (Is 25:8). Of course, Yahweh's action is replaced by the ingenuity of human brains and even more ingenious machines. Intelligence research combines with promises of salvation that were previously reserved for religion. Apocalyptic visions of the end times mutate into a computer-scientific near-term expectation.

Anthony Levandowski (born in 1980) was at google and is at Uber developing self-driving cars. But he went much further: he 'wants to program God. In autumn 2017, the entrepreneur announced that he had founded a church and now wanted to create its saviour with the help of computer codes: "If something is a billion times smarter than the smartest person,' says Levandowski, 'what else should you call such an entity but God?" That's why the founder is planning nothing less than a new religion, for which he even wants to write his own Bible: *The* Manual. In addition, there are to be religious services and places of pilgrimage.'[6]

> Pilgrimages now go not to the promised land of Canaan, but to California to the God with the nearly infinite hard drive. **Some researchers and cyborg experts believe in technologized spirituality and AI as the perfect deity of the future – and as a business model of saving the world.**[7]

The Israeli historian *Yuval Noah Harari* (born in 1976), who teaches at the Hebrew University in Jerusalem, also unfolds the vision of tech-scientists trying to become God in his bestseller 'Homo Deus'.[8] The function of religion in earlier human history was to overcome fear. The initially primitive attempts to overcome, for example, the fear of lightning through the ideas of a god hurling lightning bolts, have developed higher and higher in the course of religious history, up to monotheism. This concept overcomes the fear of the ultimate meaninglessness of existence

---

[5] Bo Dahlin: Our posthuman futures and education: Homo Zappiens, Cyborgs, and the New Adam, Futures 44 (2012), pp. 55–63.

[6] Joely Ketterer, Kann der Gott der Zukunft ein Computer sein? ZEIT Wissen Nr. 2/2018, 13. Februar 2018.

[7] https://www.qiio.de/die-goettliche-kuenstliche-intelligenz/ (last accessed 4/2/2022).

[8] Yuval Noah Hariri, Homo Deus. A Brief History of Tomorrow, 2016; he speaks of a religion of "dataism" (Chap. 11).

by giving the universe an ultimate meaningfulness. With the help of Artificial Intelligence, the history of origins can be rewritten as a history of preservation: 'In the beginning, God created the heavens and the earth. Then man created God to save the earth.' Then a human being is created who is himself God.

From the standpoint of an academically educated theology critically filtered by canonical writings, such utopian promises of salvation from a highly intelligent New Age are difficult to understand, frankly embarrassing. To engage seriously with such material almost seems to be a display of a lack of critical faculties. But one must not, as a theologian and biblical scholar, underestimate this form of a cleverly zeitgeist-mutating 'religion of intelligence.' 'An intelligent machine develops a still more intelligent machine, which in turn develops a still more intelligent machine, and on and on. The result would be an intelligence explosion and the emergence of a god-like hyper-intelligence far beyond human comprehension. Depending on who you ask, this computer god will bring paradise on earth or herald the demise of humanity.'[9] Cyborg expert Enno Park[10] (born in 1991) had this to say about it in a conversation with Deutschlandfunk Kultur on Nov. 21, 2017: 'I think that such an updated religion that deals more with our problems today, but still serves our wishes and needs as far as hope, life after death, immortality, redemption and all these things are concerned, would definitely be a contemporary thing.'[11] Will artificial intelligence give religions an update? Some researchers and cyborg experts believe in technologized spirituality and AI as the perfect deity of the future—and as a business model of world salvation. But isn't and won't such a wish remain completely illusory?

With the tremendous achievements that computer science has produced and will surely continue to produce, many top developers seem to be losing their grip. They do not seem to understand the fundamental differences between almost infinite data collection, highly complex data processing and computing power and the idea of a personal God. In my eyes, the missionaries of the new God are comparable to the people who wanted to build the Tower of Babel. They thought they were already up there with God, but ultimately had to fail; God remains qualitatively infinitely superior to these super-products of thinking machines, even to the cyborgs God must deeply 'descend' (Genesis 11:5). To make the framework of my thinking clear: I'm a tech-savvy person, I'm excited about the advances in AI that are already making their way into my daily life. I appreciate semi-autonomous driving when a distance

[9] Enno Park, Das Märchen vom Computer-Gottkuenstliche-intelligenz-das-maerchen-vom-computer-gott.1005.de.html?dram:article_id=444126, https://www.deutschlandfunkkultur.deen/artificial-intelligence-the-fairy-tale-of-the-computer-god.1005.en.html?dram:article_id=444126. last accessed 4.2.2022).

[10] Since he received cochlear implants while living on the edge of deafness for 22 years, Enno Park has called himself "a cyborg" and was one of the founders of Cyborgs e.V. in Berlin in 2013. A cochlear implant is an artificial electronic hearing that is firmly implanted in the skull and connected to the auditory nerve.

[11] https://www.deutschlandfunkkultur.de/way-of-the-future-kirche-will-kuenstliche-intelligenzals.2156.de.html?dram:article_id=401230 (last accessed 4.2.2022).

radar assists my adaptive cruise control and makes driving even safer, when a smart light illuminates the road for a very long way without blinding oncoming traffic, or when an emergency braking system detects an obstacle faster than I can myself and brings my vehicle to a stop in time in case of danger. I admire advances that provide assistance to people with a limitation, whether it is blood glucose readings by sensors instead of blood sampling for diabetics, the ability to communicate with people who suffer from amyotrophic lateral sclerosis like Stephen Hawkings, etc. Research is developing rapidly—thank goodness! But metaphysical limits remain—thank God!

3 Divine Intelligence in the Advertising Shop Window

De facto, intelligence is limited in the currently existing world, indeed it is a rather rare commodity. That is why people are looking for various ways to increase it in themselves. Whoever searches the Internet in the area of aids to increase human intelligence will immediately come across enticing advertising slogans, which I deliberately do not want to prove extensively here as a kind of surreptitious advertising; they read, for example, 'brain doping: this pill makes you smarter'. The advertisers also use religious language: 'It's time to activate our divine intelligence'. This conveys a specific image of the human being, according to which there are still enormous reserves slumbering in every human brain. Of the potentially possible performances of the grey cells, only small parts would be activated in normal everyday life. However, everyone has the opportunity to tap into the enormous reserves that have not yet been put into operation. What a happy message of salvation! A much more active and productive brain! This can be done (allegedly) by the relatively simple technique of 'transcendental meditation' originating in India and popularized by Maharishi Mahesh Yogi (1918–2008), practiced in the autohypnotic repetition of a mantra: 20 minutes in the morning and 20 minutes in the evening of autosuggestively speaking, or better thinking the mantra AOM, and the performance of the thinking apparatus is enormously increased. Or brain power is said to be enhanced by complex neognostic metaphysical thought processes, which admittedly require quite elaborate courses of study.[12] What traditional Christian practices of prayer and study (such as those of the monks) aimed at is now being replaced by Far Eastern exercises, admittedly much more oriented towards the idea of performance and economic productivity.

Divine intelligence is most aggressively advertised through psychotropic drugs. The market holds harmless globoli, but also more serious chemical substances such as Ritalin or Modafinil are available. The available drugs are supposed to reliably help to efficiently use the available resources. In the case of Ritalin, some studies claim to have demonstrated this effect in healthy people: The drug not only supports

[12] https://unitydeutschland.de/

concentration on a task in children suffering from ADHD but also increases decision-making speed in high-performance adults. Many Modafinil users also report being able to work with particular focus and endurance mentally under the influence of the drug. Artists and musicians experience that cocaine, LSD, ecstasy or mescaline increase their creativity.

That medications and drugs can really increase brain activity is undeniable. 'This is because preparations such as Ritalin and Modafinil exert their effect by interfering with signal transmission in the central nervous system. Both cause an improvement in signal transmission in the brain centres involved in attention and concentration by increasing the amount of the neurotransmitters dopamine and norepinephrine at neuron contacts. However, as soon as the intake is stopped, the effect quickly fades away,' Ulrich Bahnsen sums up.[13] The same is true for Alzheimer's drugs. Medical preparations such as Donepezil increase the amount of the brain transmitter acetylcholine in the cognitive centres. In fact, they somewhat bolster the memory of Alzheimer's patients in the early stages of the disease. But they could also be used for 'brain doping' by healthy people.

But advertising lies—as almost always. The actual effect of psychotropic drugs in healthy people is vastly overestimated. 'Overall, the effects in healthy people are on the level of several strong espressos.'[14] '*Ritalin and Modafinil* have some effect in offsetting the effect of prolonged insomnia.'[15] However, that does not stop all ways of increasing efficiency from seeming right in managerial society. 'Nevertheless, Chatterjee, the neuroscientist, believes that the *abuse of such drugs* will spread as soon as taking them becomes socially accepted. Those who get work done briskly save time; those who are at work with maximum concentration accomplish more.'[16] The harmful side effects are concealed (as was once the case with Robert Koch). This becomes particularly vivid in a poster for cannabis advertising: it shows Michelangelo's famous painting 'The Creation of Adam' under the title 'Cannabis is Medicine'. Underneath it says 'Cannabis is medicine' and 'Cannabis helps with: Loss of appetite, anxiety and alcoholism ... AIDS, epilepsy... mental illness'. Next to it, a man stands on the globe and stretches out his arms to the divine. Risks and side effects are not mentioned. But the users of so-called mind-expanding drugs are far from divine intelligence. The consumption is downright dangerous and stupid! Instead of reaching divine levels, they risk their physical and mental health and lose their freedom and become pitiable addicts.

---

[13] Ulrich Bahnsen, Die Superpille, https://folio.nzz.ch/2010/november/die-denkpille (last accessed 4.2.2022).

[14] Bahnsen, NZZ.

[15] Idem.

[16] https://folio.nzz.ch/2010/november/die-denkpille (italics M.O.) (last accessed 4.2.2022).

4 Function of God's Intelligence in the Original Context of the Bible

4.1 Old Testament

4.1.1 God as an Intelligent Creator

'In the beginning God created the heavens and the earth'—that is the first sentence of the bible. After that it is told how God brought the order of the world into existence step by step in a well-structured whole. In this mythological account, the ancient oriental knowledge of that time is condensed, without polemics, but with great reverence.[17]

> The structure of the world is of immense complexity, and yet hierarchical:4 When I look at your heavens, the work of your fingers, the moon and the stars that you have established:
> 5 What is man that You are mindful of him, And mortals that you care for them?
> 6 For You have made him a little lower than god, And You have crowned him with glory and honor.
> 7 You have made him to have dominion over the works of Your hands; You have put all things under his feet (Psalm 8:4–7)

In this context, the question about God's creative intelligence, i.e. about his intentions with creation, is hardly directed to the chronologically first beginning, but rather to God's presence in the current world. The fact that this world was created in such a way that it functions at all, that all factors work hand in hand as they do, that God is present in the world of man in a way that gives life and meaning—that instilled great respect in ancient man.

> Such knowledge is too wonderful for me; it is very difficult, I cannot attain to it (Psalm 139:6)

Therefore, the wise man acknowledges the superior reason of God[18] and calls himself to humble self-limitation:

> 5 Trust in the LORD with all your heart, And lean not on your own understanding;
> 6 In all your ways acknowledge Him, And He shall direct your paths. (Proverbs 3:5–6)

[17] Jan Gertz, Antibabylonische Polemik im priesterlichen Schöpfungsbericht?, ZThK 106 (2009) 137–155.

[18] Creationism is a view of the origin of the world that has come over to Europe primarily from the USA. 'The assertions of Charles Darwin are not true' – this is the basic conviction of the creationists as well as of the representatives of Intelligent Design, which otherwise unfold into a wide spectrum. For representatives of Intelligent Design, the idea is essential that there was indeed an evolution, but that this did not take place according to blind chance, but according to a meaningful, divine plan. The principle of brutal competition between species for naked survival, the 'survival of the fittest', is not the key to the reality of life and does not explain the facts. Darwin is wrong, if he wants to make the increasingly perfected adaptation to the respective habitats, the selection of the best adapted to certain ecological niches, the sole principle of a comprehensive worldview. The incredible complicated regularities and functional interrelationships of the universe and of life could only be explained by the assumption of a superior intelligence and power as cause.

This appeal does not articulate a despondent, dull, anti-Enlightenment attitude. It is not against the creation mandate that man as 'image of God' has to use his reason freely, but about *recognizing and acknowledging the limits of man's reason*. Man is empowered to subdue the earth with all his means and to establish it for the benefit of mankind and to develop it ever further. But God's knowledge of the order and purposes of creation remains infinitely superior.

Man is only 'almost like God' (Psalm 8:6); he remains ultimately *under* God. God gives him wisdom (*chokmah*

), and for this everyone is praised as 'blessed':Happy is the man who finds wisdom, And the man who gains understanding (Prov 3:13; cf. Prov 2:2f.).

But 'wisdom' in the sense of a universal insight remains withdrawn from man, even if he would like to have it differently and would like to put himself in God's place.

Biblical theism believes in an intelligence that transcends all that is conceivable and possible, insofar as it is 'supernatural,' that created the universe and is still present in it to oversee and influence the continued destiny of its original creation. As in many theistic belief systems, this God is intimately involved in the affairs of human beings. For example, he answers prayers, he is cross with bad deeds and punishes sins, he forgives guilt, when it is confessed, and he intervenes in the world by performing miracles. The implication is to trust divine intelligence more than one's own. But this is not an implicit call to spiritual inactivity or self-degradation.

On the contrary, the Old Testament has a very differentiated and subtle relationship to critical philosophy: in current Old Testament research, the significance of the wisdom traditions, some of which are extremely 'free' in their thinking, is increasingly valued more highly. I would like to call this process 'sapientialization,' by which I mean the more intensive penetration of the pious tradition with intellectual categories of wisdom. In the course of its history, the religion of Israel made a move in the direction of a philosophical sound (which, incidentally, continues in the history of Judaism up to the present day). This sapientialization can be observed not only in view of the five 'textbooks' of the Bible, the 'Pentateuch of Wisdom' (Proverbs, Job, Kohelet, Jesus Sirach, Sapientia Salomonis), but also in the context of the historical books and the prophetic writings, even in view of the final editing of the Pentateuch and the Psalter. The history of this movement of thought, however, is by no means sufficiently researched. In all areas of human reality—history, law, ethos, ritual and prayer—the faith of the Old Testament has opened itself—sometimes of necessity and reluctantly—to skeptical reflection and has entered into tense dialogues with 'autonomous', i.e. experiential, thought. The tensions between traditional religious doctrine on the one hand and self-experienced individual reality on the other hand are intensively perceived and thematised in the exilic–post-exilic period. However, this does not cause a 'crisis of wisdom,' as this period of wisdom development in Israel was traditionally called in literary history. Rather, in my view, this disruption of pious tradition, this seemingly deficient mode of religion, causes precisely a '*flowering of wisdom.*' Job 28 is a very appropriate example of this. Those who consider this text in the context of critical self-reflection and self-limitation will easily understand: He does reflect on the limits of wisdom, but precisely in so doing gains room for a humble practical faith. A text like Job 28 with its critical attitude towards knowledge is not a testimony to the ‘failure’ of wisdom, but on the contrary, a climax of the critical Jewish ‘philosophy of religion’ contained in the Old Testament.

The following translation of the four passages will endeavour to be as literal as possible, in which the uncertainties and obscurities will not be glossed over. They will require a concise exegesis. The structuring headings are mine.*I. Man has tremendous possibilities*
1 Surely there is a mine for silver,
and a place for gold o be refined;
2 Iron is brought out of the earth,
and rock, it melts into copper.
3 Man puts a limit to darkness;
and he, he searches to the utmost limit the rock of darkness and the shadow of death.
4 He breaks an end far from where you live;
Those who are forgotten, without support for the foot they hang, far from the people they float.
5 The earth from which bread comes forth,
their lower parts are stirred up as by fire.
6 Its stones are the place of the sapphires,
and gold dust is found in it.
7 A path unknown to the bird of prey
and which the eye of the red kite has not seen, -
8 The proud wild animals have not trodden it,
the lion hath not passed over it.
9 He puts his hand on the hard flint,
He overturns the mountains at the roots.
10 He drives channels/tunnels into the rocks,
and everything precious sees his eye.
11 The sources of the rivers they probe;
and their secret he brings out into the light.
II. The most precious thing eludes man
12 But where can wisdom be found,
and where is the (finding) place of understanding?
13 Man does not know their layer,
and it is not found in the land of the living
14 The deep says: 'It is not in me,'
and the sea says: It is not with me!
15 refined gold cannot be given for them
Nor can silver be weighed for its price.
16 It cannot be valued in the gold of Ophir,
with precious Schoham stone (onyx/carnelian?) or sapphire.
17 Gold and glass cannot equal it,
nor can it be exchanged for jewels of fine gold.
18 The coral and the crystal are not thought of at all,
and a bag(?) of wisdom is worth more than pearls.
19 Its value is not comparable with topaz from Kush;
nor can it be valued in pure gold.
20 ut where can wisdom be found,
and where is the (finding) place of understanding?
21 Veiled is she from the eyes of all living,
and from the birds of the air it is hidden.
22 The Abyss and Death say:

'We have heard a rumor of it with our ears.'
III God alone has access to wisdom
23 *God understands its way,*
And He knows its place.
24 For he looks to the ends of the earth.
Under the whole heavens he looks,
25 When he gave to the wind its weight,
and apportioned out the waters by measure;
26 When He made a law for the rain,
And a path for the thunderbolt;
27 Then he saw it (wisdom) and declared it;
he established it, and searched it out.
IV. What remains for man*?* The fear of God!
28 And he said to humankind,
'Truly, the fear of the Lord, that is wisdom
and to depart from evil is understanding.

The imagery of verses 1–11 is taken from mining. Full of admiration it is stated that man is able to advance into quite remote areas. The thematic keywords are 'find' and 'place, site' that run through the text (vv. 6.12.20). V. 4 is enigmatic, but it seems to describe the outlandish attitude with which a miner sometimes works his way forward in the tunnels. This dirty work produces brilliant results. If one knows that this level of imagery is to become a comparative donor for the field of philosophy, then there is something downright comical about the text. He who searches in the depths of thought for the gems of reflection is like one who 'dangles' far from men between the upper world and the underworld, and must get downright dirty before he advances to the valuable. However, despite all the hardships and necessary contortions, technology exudes a great fascination. What man can do! He can do more than all animals; sees deeper, penetrates into the most inaccessible regions (v. 7 f.). Considering the mines, excavated by Israeli archaeologists at Timnah and in the southern Aravah valley or by Jordanian archaeologist in the Edomite Wadi Faynan, 'He turns the mountains from the root' (v. 9b) is not an exaggeration. Perhaps, however, the author is referring to descriptions of mining in (Upper) Egypt (cf. 'Cush' in v. 19) where the numerous mineral resources were mined on a larger scale. But the question whether there is any real mining in view at all, and where exactly it would be located, does not play the decisive role. Even if the author has no real view, the opening stanza vv. 1–12 radiates *deep admiration for man*! Whatever treasures may be hidden in the earth, 'all precious things his eye sees' (v. 10) and 'their secret he brings out to light' (v. 11).

In contrast, the second stanza, again with eleven lines, begins with a critical drumbeat. In finely prepared contrast, the keywords 'place of discovery' and 'place, site' from v. 1 are taken up again in v. 12, but now a negative statement is rhetorically impressively marked. The deposit of wisdom is unknown; indeed, it is not to be found 'in the land of the living' (v. 13). But even the (personified) underworld and the sea can give only negatives (v. 14): 'Here it is not.' Vv. 15–19 turn the gaze from the place to the 'value of wisdom.' A statement of value is not possible. The most precious things are not valuable enough to outweigh wisdom. Just as God Himself cannot be adequately represented by anything earthly, neither can wisdom.

Her nature is akin to that of God: V. 21f. emphasize her veiledness to all living things. Just as God was only ‘hearsay’ to Job, so was Wisdom. The third stanza (vv. 23–27) unfolds the kinship of wisdom and God from another angle: Only God has wisdom, exclusively He knows its place and the way to it; wisdom is God’s. Man can dig as much as he likes, he will never attain wisdom. The description of how God meets wisdom is especially interesting. The terms of vv. 23–27 are polyvalent, oscillating between past and present. God saw wisdom then at creation, but he also sees it anew each time he gives ways and order to the ‘wind, lightning, and thunder.’ In his act of creation, God keeps and maintained contact with wisdom. Assuming that all four verbs in v. 27 are logically compatible, the terms describe what an ancient scientist is supposed to do, and in this they are remarkably modern: God himself realizes the ideal of science: to look closely, to count, to put down, and to examine.

After God then and/or now respectively has ‘studied’ wisdom anew, he spoke it ‘to man’ (or Adam?). It is this closing verse that matters now. The question of God’s justice cannot be answered. Such divine wisdom would be necessary for the solution of the question of theodicy, but it is unattainable. God, who is portrayed as a studied knower of wisdom after v. 27, has ‘merely’ passed on a *particulum veritatis* from the fullness of his knowledge after v. 28. That man has no access to cosmological wisdom cannot actually be meant, since vv. 1–11 sing an impressive hymn to man’s vast possibilities. Man can and does know much-technical things. But behind this technical mastery of the world, another quality of wisdom shines forth. The ‘place of wisdom’, to which there is no access for man, respectively the ‘abode of insight’, which is not accessible to man, point in another direction. For interpretation one could—slightly anachronistically—fall back on Kantian philosophy and say: Job 28 distinguishes between the world of phenomena and that of noumena, the appearance and the ‘thing in itself’. Knowledge of the higher things must be abolished to make room for faith. Less anachronistically, Hi 28 might be compared to the Platonic doctrine of ideas, knowledge of which can be presumed with reason in Israel for the time of the chapter (c. 350–250 B.C.), at least in vulgarized form. What God says to man is not a ‘feeding off,’ a weak substitute, a ‘surrogate’ for the actual. Rather, v. 28 expresses a view of man that can only be adequately described by the term ‘dialectic.’ Such is man and, accordingly, his wisdom: truly formidable and at the same time limited. Impressively profound and at the same time restricted. Limited in the theoretical and at the same time called into absolute responsibility by God in the practical.

The insight that the intelligence of God is an important part of the Old Testament image of God was first encountered by me in Bernhard Lang[19]: Here Lang distinguishes five images of the God of the Bible: Lord of Wisdom, Lord of War, Lord of Animals, Lord of the Individual (the personal God) and Lord of the Harvest. He clearly takes his cue from Plato’s Politeia, where the nourishing state, the state of

[19] Bernhard Lang, Jahwe—der biblische Gott. Ein Portrait. Munich 2002, pp. 30–64.

defense, and the teaching state are differentiated. He relates this again to the parts of the body:

Nutrient stand	Defence stand	Teaching Stand
Lord of the animals, Lord of the harvest	Lord of war	God as the Lord of Wisdom
Belly	Legs	Head as part of the body of God

Of the various aspects and spheres of activity of the biblical God, Lord of Wisdom concerns the highest realm, the level of control and direction. Speaking with Plato on the level of government: God as lawgiver, God as covenant ruler, God as king, God as scribe, God as strict accountant. Lord of Wisdom refers to the image of God at its upper level: 'The Judean scribes created an image of God based on their own ideals of wisdom, diplomacy, law, and writing. Their God is the Lord of the covenant, the law, and the book. Later, in the word 'Torah' ('instruction, law') was summed up what constituted the Jewish religion. ...Israel became the 'people of the book,' the textual community; the highest wisdom and the deepest knowledge were acquired not by independent observation of the world and man, but by interpretation of a written document inspired by God. Expressions like 'book religion' 'law religion' or 'revealed religion' point to the same central fact: the covenantal order revealed by God and recorded in a book forms the basis and centre of biblical theology.'[20]

This image of God has a power to shape culture: the highest and most important thing about God (like culture) is the realm of control, of science, of the intellectual. This aspect of God moves religion strongly into the proximity of enlightenment, penetration and domination of the world.

In order to grasp the different dimensions of the image of God as the 'Lord of Wisdom' in a more differentiated way, one could draw on a comparison in the history of religion. Thereby it is extraordinarily striking that in the cultures in the environment of the Old Testament *wisdom* is often connected with *a goddess*. In ancient Mesopotamia, *wisdom is* encountered *as a woman* or *as the goddess Nina*: Nina is the Sumerian city goddess of the place Nina near the city of Lagash. She is considered the fertility goddess of springs and canals, but also the wisdom goddess of oracles and the interpreter of dreams. She is the daughter of Enlil and the sister of *Ningirsu* and *Nisaba*. Her symbolic animals are the scorpion and the snake. *Nisaba* is a goddess of writing, thus a goddess of the sciences, including architecture. The Egyptian goddess *Ma'at is* consubstantial with *Pallas Athena, who* was born from the head of Zeus and combines knowledge and war strategy.

This strong connection between wisdom and female divinity is also echoed in the Old Testament. In the Wisdom Sayings of Solomon (Prov 1–9), a remarkable opening of the God of Israel to the wisdom

[20] Lang, 60.

goddess takes place. 'Lady Wisdom' delivers long speeches and courts the reading young men by describing her multiple functions (Prov 8:14–31):14 Counsel *is* mine, and sound wisdom;
I *am* understanding, I have strength.
15 By me kings reign,
And rulers decree justice.
16 By me princes rule, and nobles,
All the judges of the earth.
17 I love those who love me,
And those who seek me diligently will find me.
18 Riches and honor *are* with me,
Enduring riches and righteousness.
19 My fruit *is* better than gold, yes, than fine gold, A
nd my revenue than choice silver.
20 I traverse the way of righteousness,
In the midst of the paths of justice,
21 That I may cause those who love me to inherit wealth,
That I may fill their treasuries.

This eulogy of Lady Wisdom finds its climax in the description of her role in the primeval creation of the world.22 YHWH possessed me at the beginning of His way,
the first of his acts of long ago.
23 In the primeval times I was formed,
from the prehistoric times of the earth.
24 When there were no depths
I was brought forth,
[...]
30 Then I was beside him, like a master worker;
and I was daily his delight, rejoicing before him always,
31 Rejoicing in His inhabited world,
And my delight was with the sons of men.

Woman Wisdom was *formed from* eternity, 'from the beginning'; thus she is *under* God. However, she was present at the work of creation itself. It probably remains a mystery what *amon* in Prov 8:30 means exactly; whether 'womb child' or 'architect.' In any case, Lady Wisdom here does not represent a real goddess (such as Maat or the like), but is understood merely as a 'rhetorical figure,' a 'goddess of the moment' who has no metaphysical quality of being, but only a poetic one. She is a symbolic figure for the power that already indwelt and attended God in the *creatio prima.* The whole tendency of the chapter is a self-praise of wisdom, an advertising speech that wants to emphasize its influence, power and decision-making competence by referring to the extreme age of wisdom.

4.2 The Old Testament View of Wisdom in Cultural–Historical Comparison: Job Among the Philosophers

I would like to underpin this dialectical view of the human being with a cultural–historical comparison which, in my opinion, is still paid too little attention in research. One is Socrates, the other Sophocles.

The one who in antiquity was almost emblematically regarded as the representative of the insight into the limitedness of human knowledge was Socrates. In the Old Testament research, the connection from Hi 28 to Socrates has very rarely been drawn, hinted at for instance by Carroll A. Newsom[21] 'I know that I do not know'—using this insight, Socrates repeatedly opposes the arrogant conceit of the illusory philosophers discussing with him. From supposed clarity, Socrates leads his interlocutors, the sophists, repeatedly to the insight that their certainties are uncertain. This is a core idea of, for example, the Apology of Socrates

> :But this one thinks he knows, since he does not know, but I, as I do not know, so I do not mean it either. So I seem to be wiser than he by this little, that what I do not know I do not think I know. (Platon, Apology, 21d)

This knowledge about the ignorance concerning the actual being Socrates does nowhere summarize in the speech of the 'place/residence of wisdom'. I could not find a phrase like Hi 28 in the Corpus Platonicum. However, related ideas can be indicated. In the central parables of the Politeia, the parable of the sun (506b–509b), the parable of lines (509c–511c) and the parable of the cave (514a–519b), the distinction between appearance and the ideas behind it is mythically impressively unfolded. The path from the superficial shadowings to the fullness of being is an arduous ascent, possible only for a few philosophers. Job 28 is more radical than Socrates. The 'locus intellegentiae' (as the Vulgate translates it) is withdrawn from man altogether. The Book of Job is skeptical of all Socratic hope that philosophical education could lead man to the knowledge of truth, beauty and the good. There remains for 'man' only the reference to the fear of God and the strict avoidance of evil. Thus, the Old Testament spares itself Platonic theories such as the assumption of reincarnations, of amnesias in the incorporation of the soul or of 'feathered souls'.

A Greek comparative text that bears a striking structural analogy to Hi 28 is the choral song of the Theban ancients from Sophocles'

> (496–406 BC) Antigone: [332] Wonders are many, and none is more wonderful than man. [335] This power spans the sea, even when it surges white before the gales of the south-wind, and makes a path under swells that threaten to engulf him. Earth, too, the eldest of the gods, the immortal, the unwearied, [340] he wears away to his own ends, turning the soil with the offspring of horses as the plows weave to and fro year after year. Sophocles, Antigone, verse 323ff.[22]

This choral song, like the whole of Antigone, is an important theological text, a small anthropological treatise with great impact. Just as in Job 28, the astonishing greatness of man is first emphasized: he has mastered seafaring, agriculture and animal husbandry, he has mastered hunting, he has mastered rhetoric and philosophy, and then suddenly, in the middle of the verse, he emphasizes man's lowliness with a play on words: 'all-wise unlearned he comes to nothing'. Why this scepticism in the face of man's overwhelming greatness?—Because he cannot answer the

---

[21] C.A. Newsom, Dialogue and Allegorical Hermeneutics in Job 28:28, in: E.J. van Wolde (ed.), Job 28: Cognition in Context (Biblical Interpretation Series 64), Leiden 2003, 299–305, here 300.

[22] Sophocles, The Antigone of Sophocles. Edited with introduction and notes by Sir Richard Jebb, Cambridge. Cambridge University Press. 1891.

crucial questions of life and death! ‘To escape the realm of the dead alone he does not know.’ Sophocles’ text seems in some ways representative of Greek anthropology. Man has limits set for him by God. This is tragic. The mighty Oedipus has become the murderer of his true father and the husband of his birth mother precisely by fleeing from his (supposed) parents. Thus, his glorious daughter Antigone will also fail tragically.

Through the comparisons in the history of religion and cult it becomes even clearer: The song of wisdom in *Hi 28 is an expression of a radically critical philosophy*. The full wisdom is withdrawn from the human being as well as the access to the essential. ‘I only see that we can know nothing’ says the Job poet. He thus resigns himself to the question of theodicy. It is theoretically unsolvable. This critique of pure reason, however, does not lead to speechless resignation, but to an esteem for practical reason. Job thus rightly belongs among the philosophers.

4.3 New Testament

Analogous to the Old Testament, the New Testament

> critically questions ‘the wisdom of this world.’ In Paul (1 Cor 1,18–24) you can read:18
> For the message of the cross is foolishness to those who are perishing, but to us who are being saved it is the power of God.
> 19 For it is written: ‘I will destroy the wisdom of the wise, And bring to nothing the understanding of the prudent.’
> 20 Where is the wise? Where is the scribe? Where is the disputer of this age? Has not God made foolish the wisdom of this world?
> 21 For since, in the wisdom of God, the world through wisdom did not know God, it pleased God through the foolishness of the message preached to save those who believe.
> 22 For Jews request a sign, and Greeks seek after wisdom;
> 23 but we preach Christ crucified, to the Jews a stumbling block and to the Greeks foolishness,
> 24 but to those who are called, both Jews and Greeks, Christ the power of God and the wisdom of God.

This profound plea for the cross implies a critique of the wisdom of the wise, the ‘cleverness of the clever’. Of course, this is not originally aimed at Google developers, and yet it is justified to apply this interpretation of the world to the discussion of AI in the present circumstances. There is nothing violent about an application aimed at the present. People want to build a tower that reaches to the heavens, they want to build a computer that becomes God itself. But, ‘Has not God exposed the wisdom of the world as foolishness?’

Rather than redeeming oneself with super-achievements, the New Testament holds that true wisdom is in God: ‘But for those who are called, both Jews and Greeks, we preach Christ, God’s power and God’s wisdom.’ (1 Cor 1:24)

5 Conclusion

In principle, the Bible is very science-friendly: 'Subdue the earth!'—this includes the exploitation of all technical possibilities. The biblical writers would be happy and excited about the enormous computer-technological achievements of the twenty-first century. (Partially) autonomous driving, care robots, automated production lines and much more can be very beneficial. However, humans must remain humans! Those who demand critical thinking and find a God in the form of a supercomputer embarrassing are not anti-science, but quite the opposite. For science also involves reflection on the limits of thought and on the limits of what is possible. That is part of the responsibility of science.[23]That is part of what makes theology a science. As a symbolic illustration of this thought, I would like to consider a grave monument of natural scientists in the space of the church: Isaac Newton (1643–1727) and Charles Darwin (1809–1882) found their final resting place in London's Westminster Abbey, and in 2018 they were followed by Stephen Hawking (1942–2018) (see Fig. 21.1).

Faith and critical, enlightened thinking belong together. The Intelligentia Dei dwells in the church (not only in the Westminster Abbey, but in general in every church), it lives there together with the principles of physics (inertia principle, the action principle and the interaction principle of Newton), together with the theory of evolution (Darwin) and modern astrophysics (Hawking). And maybe someday the inventors of google will be buried there too. But Intelligentia Dei does not merge in all science, but also preserves its otherness. Many natural scientists know this, too; Albert Einstein is quoted as an example:

> To feel that behind what we can experience there is hidden something inaccessible to our minds, whose beauty and sublimity reach us only indirectly and in faint reflection, that is religiosity. In this sense I am religious.[24]

Finally, I'll take the liberty of focusing on one object as *pars pro toto*: my mobile phone. I admire what a modern smartphone can do, and I always want to have the latest model. I'm fascinated by the miniaturization of artificial intelligence. I get excited when I can now carry 1 terrabyte of memory in my pocket and download my entire cloud at lightning speed via fast 5G network, when I can be connected to my colleagues and friends all over the world via video telephony. When I can listen to millions of music tracks and watch movies at any time, when I can access the university library for research literature digitally, and so on and so forth. It is already fantastic. In addition, the developments are advancing rapidly. Moreover, if one day these capabilities of my phone can be 'docked' to my body and brain, then I

[23] Cf. paradigmatically Hans Jonas, Das Prinzip Verantwortung. Versuch einer Ethik für die technologische Zivilisation, Frankfurt 1978; new edition with an epilogue by Robert Habeck, Berlin, 2020. Jonas' categorical imperative is: "Act in such a way that the effects of your action are compatible with the permanence of genuine human life on earth" (Das Prinzip Verantwortung, 36).

[24] Albert Einstein's spoken creed, probably spoken on record in 1932, reprinted in the journal 'Die Naturwissenschaften' 53 (1966) issue 8, p. 198.

Fig. 21.1 Grave of Isaac Newton, the great physicist, in Westminster Abbey, London (Isaac Newton grave in Westminster Abbey, photographed by Klaus-Dieter Keller on 17.6.2006 (public domain); (https://de.wikipedia.org/wiki/Isaac_Newton#/media/Datei:Isaac_Newton_grave_in_Westminster_Abbey.jpg) (last accessed 28.5.2021).)

probably—after ample consideration and reassurances—would not refuse it. But there's one thing I would still never say to my cell phone: 'My God'. Machines and their inventors should be humble and should always know their place.

The ancient notion of exclusive divine intelligence cannot be empirically verified; there is no proof adequate to scientific practice. However, with a little thought, one can nevertheless get a *prevision* of it from various indications. This religious hunch—especially in its biblically developed form—finally proves to be a very meaningful, even necessary enlightening corrective against a crazy, totally illusory and self-overestimating belief in technology.

Manfred Oeming is Professor of Old Testament Theology at the University of Heidelberg since 1996; previously, he taught in Bonn, Mainz and Osnabrück. From 2002 to 2006, he was director of the College of Jewish Studies in Heidelberg. Since 2004 he has been conducting annual excavations in Israel in cooperation with Tel Aviv University, first in Jerusalem (Ramat Rahel), since 2012 in Aseka. His publications enclose exegesis of Old Testament books (especially Job and the Psalms), theology and hermeneutics of the Old Testament, archaeology, and border issues between biblical studies and philosophy and psychology. In 2019 he received an honorary doctorate from Charles University in Prague.

Chapter 22
Political Intelligence? A Practical View Between Politics and Science

Theresia Bauer

Abstract A report on the practice of political action and decision making under the conditions of a pandemic.

1 A Situation Report

It is April 2021. We are in the middle of the third Corona Wave. This is what the science says. This is what the politicians say. The facts are on the table. Yet this is often where the agreement ends. Rarely has it been so unclear as to what the right thing is to do. Seldom has it been so obvious when politicians act hesitantly and when their many small steps often seem to lack direction or even be contradictory. The public debate on this is no longer just complex and controversial, it is increasingly resentful. Politicians seek to avoid responsibility; and the search is out for those responsible, or even just scapegoats, for the burdensome situation. Rarely has consistent and courageous political action with a clear direction been so necessary.

It is April 2021. We are in the middle of coalition negotiations to form a new government in Baden-Württemberg for the next 5 years. It should be stable and capable. It should place ambitious and rapidly effective climate protection at the center of its actions. At the same time, public funds are limited due to Corona. However, time is running out to deal with the great task of our time and to avert a global disaster for our planet. This is what the science says. This is what the politicians say. The facts are on the table. Yet this is often where the agreement ends.

What is the right thing to do and what is the right tempo? An enormous expectation has been built up by the public, forced by the pressure of protests from children and young people on the streets. And the Federal Constitutional Court has confirmed it by condemning the federal government's climate protection law as being too unambitious, because it endangered the next generations' potential for action and rights of freedom. Federal policy must be improved.

T. Bauer (✉)
Ministry of Science, Research and Arts Baden-Württemberg,
Stuttgart, Baden-Württemberg, Germany
e-mail: eric.miller@mwk.bwl.de; http://www.mwk.baden-wuerttemberg.de

R. M. Holm-Hadulla et al. (eds.), *Intelligence - Theories and Applications*,
https://doi.org/10.1007/978-3-031-04198-3_22

At the same time, fears are growing among the population of profound changes in the face of the transformative dynamics of digitalization, artificial intelligence, and scientific progress. Companies, families, educational institutions, our society as a whole are under enormous stress to adapt. Rarely has consistent and courageous political action with a clear direction been so necessary.

There are two current fields of action in which political intelligence is particularly in demand, and where the public is particularly vocal in its doubts about whether there is enough political intelligence to solve these problems. Ranting about politics is certainly part of the background noise of public debate in this country. It is easy to rant about the supposedly overwhelmed politicians and their alleged inability or unwillingness to do their jobs well. Journalists, YouTubers, and the professional consulting industry also provide countless suggestions and unending advice on how to conduct politics more intelligently, as a professional craft, so to speak. There is no shortage of ideas on how strategy and tactics work in politics and how success can be achieved both internally and externally. Probably precisely because politics as a whole is suspected of not delivering what is needed. At the beginning of the pandemic, a great many people actually had growing confidence in politics in the short term. In recent months, this relationship has reversed and deteriorated massively. Decisive and intelligent action is now urgently needed so that the Corona crisis and the climate crisis do not develop into a crisis of trust in democracy.

In remarkable contrast to the low public esteem in which politics is held today is the respect for politics and its demanding requirements throughout the history of political and philosophical ideas. This is also reflected in the scholarly debate about intelligence.

As “ethical-moral,” “communicative,” or “political” intelligence – some also call it “wisdom” – these manifestations of intelligence are assessed as particularly complex and ethical-political action as the highest form of intelligence. Political intelligence must bring together the different dimensions of intelligence and direct them toward the common good and shared values. Political intelligence must produce an inter- and intrapersonal understanding of problems that points beyond the single individual and locates itself in larger contexts – and political intelligence must be measured by how one acts concretely in practice. Political intelligence must aim at doing the right thing at the right time with a view to the common good.

One occasionally hears from experts: “Politics is the art of making the necessary possible.” How can the conditions for the success of political intelligence understood in this way be improved? And how can this scarce resource be increased?

More science in politics would be a simple answer. It is plausible, but it is also overly simplistic. Scientific evidence must, of course, play a role in the policy-making process. After all, good policy decisions must be as evidence-based, rational, and reflective as possible. As far as possible, they should be made on the basis of established facts and diverse disciplinary perspectives. Enlightened policy cannot succeed on the quicksand of ignorance. That is why it is undoubtedly worth every effort to make existing knowledge even more accessible and usable for political debates and decision-making. I agree that there is room for improvement in terms of scientific policy advice. This applies to parliaments as well as to governments at all levels.

One example: Last year, when the management of the Corona pandemic was a permanent challenge for the federal and state governments, the Kretschmann government regularly invited scientists, mostly from the medical field, to our cabinet meetings. All cabinet members were thus given the opportunity for a direct fact check. In addition, scientific advisory panels were established in ministries. These new “contact areas” between science and politics were very helpful in quickly obtaining initial well-founded assessments in the confusing situation and in addressing open questions in dialogue. It has also led to the identification of concrete research needs in individual cases and the rapid launch of corresponding research projects with support from the state. As Minister of Science, I was particularly impressed by a second aspect: these meetings were suitable for developing a deeper understanding among the members of the government of how science deals with what it does not know or what it does not yet know. Everyone around the table was able to experience the caution and precision with which serious scientists, in the interest of their credibility, endeavor to repeatedly illuminate the limited scope of their statements. How aggressively they deal with the fact that their research always moves on the borderline of the unknown and not yet understood – and must move if it really wants to produce something new. And how decisions considered correct at an earlier stage have to be revised when new findings are presented. What a difference from political self-understanding and discourse! Of course, our decisions are just as much a constant groping, reworking, correcting, a constant process of learning and adapting to new circumstances and requirements. In my 10-year term as Minister of Science alone, the State Higher Education Act has been amended 15 times.

Politicians are expected to make their decisions particularly quickly, because we have to deal with problems and solve them as quickly as possible. We are also accustomed to a different linguistic style, one that attempts to maximize the certainty and clarity of decisions in communication. In other words, in politics we do not usually disclose the provisional nature and limited scope of our decisions. Presumably, citizens would be quite disturbed if we explained at length the uncertainty, limited knowledge, and time pressure that accompany our decisions that must nevertheless be made. In any case, even the best advice from serious science cannot free us as politicians from these framework conditions.

This is not to say that politics is fundamentally fast and science is slow per se. Last year we witnessed the tremendous speed with which science provided new insights into the pandemic. Science has impressively demonstrated its ability to share and increase knowledge globally. Vaccines have been developed in a very short time, and these are now the most important key to freeing our coexistence from both burdensome and necessary restrictions in the foreseeable future. However, in order for science to be able to unfold this power in concrete terms, it needs a lot of time in advance. This much is certain: science needs the freedom to think in the long term. Without basic research and without established structures of scientific cooperation, the scientific “output” of recent times would not have been feasible.

In politics, we are constantly driven by short-term pressure to react immediately and to have a well-founded opinion on everything and everyone. But the result is by no means always quick and clear decisions. It often takes time for political action to mature and be implemented. And it is not always obvious to everyone whether a decision has been taken in the right direction. In my experience, however, this has least to do with a lack of the necessary knowledge. It has to do with the complexity of the process: politics has to integrate different perspectives and interests and, as a rule, organize majorities and negotiate compromises. It has to take into account effects on different areas of society. It must be convincing and comprehensible both internally—to one's own political "collective"—and externally—with regard to political competition—and not least with regard to the public. And it must always do so within the constraints of scarcity, especially limited financial resources. As government policy, it must translate what has been decided into good administrative action. A political decision therefore needs many people who are convinced of a jointly negotiated decision and who want to implement it properly together.

That's why it is usually complex to understand in detail why things aren't progressing faster and better: Why haven't our houses been shining blue in the sun for a long time now, because photovoltaic systems on roofs have become the new normal—at the very least on state-owned buildings? What was the reason that Germany did not have a faster and more effective vaccination strategy? That it nevertheless succeeded in limiting the spread of infection and especially the severe case developments and death rates comparatively well.

Politics is action. Politics in a democracy is joint action. In other words, being able to agree on doing something new together. Hannah Arendt also defines the subject of power with such an understanding of politics: it is the human ability to be able to begin. The ability to set change in motion. In a democracy, this can never be achieved by individuals alone but only by many who rally together behind an idea. Political intelligence, understood in this way, grows with the ability to act collectively.

In this sense, can science contribute to making politics more intelligent? Absolutely! The world of science can help the world of politics to act in a more fact-based, rational, and consistent way. Does replacing the world of politics with the world of science make it smarter? Not at all. For the meaning of the political is entirely different from the stubbornness of the sciences, which seek truth(s). Doing the right thing at the right moment in terms of the common good is quite different from bringing about world understanding and new knowledge. These different logics of the two worlds cannot be exchanged. But they can enrich and improve each other through more "transfer": As a politician and as a Minister of Science, it is therefore a particular concern of mine to ensure more potential "contact surfaces" and a "higher conductivity" between the two logics.

A look at history shows that in times of crisis, the people's trust in their governments often declines the longer the crisis lasts. In turn, desire to be governed by experts or technocratic councils flourish, because in this way pure expertise would supposedly count instead of political considerations. This is linked to the naïve hope of regaining the unambiguity and clarity of "technical" government action that had been thought lost, or of satisfying the need for leadership by a strong hand that offers protection and security in uncertain times.

A remarkable observation in the Corona crisis year was the opposite: science has gained recognizable relevance and visibility among the public, sometimes even great popularity. However, the public's traditionally very great trust in science has eroded considerably in recent months—mistrust has grown. That science should stay out of politics was heard more and more often.

In the past few months, science has publicly and visibly entered into the political process of wrestling with the unknown and dealing with uncertainty. It is therefore not suitable as a lifeline for those frustrated by politics to (re)obtain simple certainties and supposed security. Perhaps this is why science is now suspected of conspiring with politics.

A further motive is added when the accusation is raised that science is moving beyond its own terrain into the field of politics. We know this motive from the debates about human-made climate change and the facts that have been presented by science for years. We know the angry public attacks on science for confronting the public and politicians with what we feel are unpleasant truths. They still ring in all our ears as the ugly accompaniment to the Trump era, now thankfully history. But let's not kid ourselves: here in Germany, too, anti-scientific or even pseudo-scientific babble has gained ground and continues to challenge us.

Science that gets involved in social controversies gets itself caught up in the whirlpool of public controversy. Even if it proceeds with all seriousness and credibility and contributes only "its own" with the greatest possible precision, namely assured knowledge and rationally founded understanding. This price is worth it. For a liberal democracy thrives on the fact that the search for the right stance, for the right priority, for the right path, and for the justifiable risk is always a process of public struggle. This is precisely what distinguishes political action in a liberal democracy from that in an authoritarian regime. Our political action and our ability to begin can only flourish when many are in the know, when they have formed an informed judgment and acquired a conviction. Courageous, consistent, and clearly oriented political action only has a chance if it is supported by an enlightened and self-confident society. How could this be achieved without the contribution of science?

In return, politics and the public are obliged to always listen to the voice of science not only when it suits them and gives their own convictions more clout. The authority of the scientific argument must be taken into account precisely when the scientific perspective challenges one's own point of view and what has gone before. This can lead to hard conflicts, as I can also report from my own experience: For years I have been irritated by the fact that the regulation of genetic engineering in Europe do not go hand in hand with the current state of science. Here, perspectives urgently need to be brought together. Unfortunately, it has been seen time and again that the scientific view of genetic engineering carries much less weight in the political mix than political and economic interests. This must change as a matter of urgency. Fortunately, a recent study by the EU Commission has now reopened the debate. If we want to take better account of the voice of science in relevant issues for the future, then this must apply independent of the respective political motives and interests of one's own person or environment!

More active communication and transfer from science is therefore not only required with regard to direct contact areas with political decision-makers. It is just as important in the direction of the public, in the direction of the citizens who are interested in our coexistence and our common future. Our society needs the expertise of science. It needs the universities as a space in which the established is critically examined without interruption, in which new insights are developed and deepened. Our universities are needed as a space in which the next generation learns and experiences how rational, fact-based, and reflected examination of our world and the tasks at hand works. Our universities are needed as a space where people are empowered to face relevant problems, to find solutions for them, and not to run away from them.

We also need more and faster transfer from science to the economy and local structures: where transformation becomes concrete and where the future takes shape in innovative products, processes, business models, and in changed social practice. If this transfer process functions well, then another important prerequisite for intelligent politics is created: for it is not the top-down decision of politics that successfully brings the new into the world, but it is the active connections at the interfaces of business, society, science, and politics that productively accelerate innovation processes. The state government has created various formats for this purpose to develop these contact areas more systematically: Strategy dialogues have been established on the major transformative topics that particularly affect our strengths in Baden-Württemberg. Business, science, civil society, and politics come together in a regular top-level dialogue in which we agree on goals and measures for the future of our automotive industry and for the further development of Baden-Württemberg as a health center. This will be supplemented by a strategic dialogue on innovative construction and planning.

As a further pillar of this policy, we are focusing on innovation campuses with international appeal: We support those places in Baden-Württemberg where a special quality and density of science and research, companies and start-up activities come together to work on future fields and strategically cooperate to become attractive for talents and ideas from all over the world. This has been achieved in the Tübingen/Stuttgart area with Cyber Valley, which focuses on artificial intelligence and machine learning. In the same way, we support the special potential in Heidelberg/Mannheim with the promising "Health and Life Science Alliance." With its international research excellence, the region has what it takes to have an impact even further beyond the state's borders and to provide groundbreaking impetus for business and health. Seen in this light, political intelligence is also the ability to promote structures that make it easier to get started by bringing together enthusiasm and know-how for renewal.

In other words: political intelligence lives from preconditions that politicians cannot create on their own. It lives from the power of judgement, the sense of responsibility, and the ability of many to face the tasks of the present and the future. Good persuasion, feasible solutions, the persistent securing of majorities and resources is essentially our business as politicians – and it undoubtedly requires some political intelligence. However, it can only really succeed on a broad common basis. This can certainly not be achieved without the help of science.

In Germany, we do not have the institution of a *Scientific Advisor to* the government, but we do have many formats that bring science, business, and politics together. And that is why I like US President Biden's maxim, which he formulated recently when he was appointed, so well for our policy:

> "Science will always be at the forefront of my administration – and these world-renowned scientists will ensure everything we do is grounded in science, facts, and the truth."[1]

Theresia Bauer (MdL) is the Minister of Science, Research and Arts for the State of Baden-Württemberg.

[1] https://www.nytimes.com/2021/01/15/science/biden-science-cabinet.html (as at: 08.05.2021).

Chapter 23
Political Intelligence and Wisdom

Sebastian Harnisch

Abstract Political intelligence encompasses special forms of mental processes that enable an actor to influence their political environment in a goal-oriented way and allows them to find a solution to problems through flexible thinking and action. In this chapter, we begin by comparing the moral wisdom of Aristotle and the utility-oriented cunning of Machiavelli from a historical perspective. Then, the conceptions of intelligence of different theories of international relations and the foreign policy of states are discussed based on current examples. Finally, we critically reflect on the extent to which political intelligence should be re-thought in an era of a '*broad present'* (Humbrich)—in which the importance of the past and the future is increasing in today's conceptions of politics.

1 Introduction

In modern science, intelligence refers to a special form of mental process that enables an actor to act on their environment in a goal-oriented way and to bring problems recognized in it to a solution through flexible thought and action (Draguhn, 2021). This ability is at the same time one of the oldest political virtues, linking political theory in ancient Greece (Aristotle*'s Phronesis*) and India (Kautilyas *Arthas'astrlā*) *as* well as the Christian-influenced prudence in Thomas Aquinas and Niccolo Machiavelli's reason of state aimed at the survival of the state (cf. Kersting, 2005a). It includes both, a morality in practical relationship of a politically acting person to their world and a practical and purposeful orientation towards the world, which is concerned with preservation and stability in the sense of the resilience of an existing community or the establishment of a new order.

S. Harnisch (✉)
Institute for Political Science, University of Heidelberg, Heidelberg, Germany
e-mail: sebastian.harnisch@uni-heidelberg.de; https://www.uni-heidelberg.de/fakultaeten/wiso/ipw/mitarbeiter/harnisch/

R. M. Holm-Hadulla et al. (eds.), *Intelligence - Theories and Applications*,
https://doi.org/10.1007/978-3-031-04198-3_23

The term ‘intelligence’ has a long political history and is often interpreted in terms of a categorical difference between Aristotle’s wisdom (shaped by morality) and Machiavelli’s cunning (shaped by utility) (see, for example, Sternberger, 1997). In the Western tradition, it first appears to us in Aristotle as a personal attitude that finds the right balance between conflicting cognitive—cunning and simplicity—and affective dispositions—cowardice and foolhardiness. Thus, bravery, as the right measure of political and military prudence, aims more at avoiding cowardice than at preventing foolhardiness. In addition to balancing personal dispositions, prudence is directed at the individual’s conduct of life in the community; thus, fortitude takes its place alongside justice and experience, which enable the individual to lead a moral and happy life in the community while achieving steadiness (inwardly) and reliability (outwardly) (Kersting, 2005b). Aristotle conceives of *phronesis* as prudence in a practical situation that takes all circumstances into account and is primarily directed at one’s own person. Thus, it goes beyond mere knowledge (*episteme*) and exceeds mere acting or manufacturing (*poíesis*). Additionally, *phronesis* can be directed at household and state management, since it entails a competence of self-orientation (Corcilius, 2021; McCourt, 2012).

In the Eastern tradition, political prudence is first prominently found in Kautilya’s Arthas’astra, the foundational work of Indian statecraft from the fourth century BC, which in the twentieth century demonstrably influenced Max Weber’s thinking on power as much as Hans Morgenthau’s thinking on the balance of power (Mitra & Liebig, 2016). Political wisdom, here, is shown through the correct use of (physical) coercion and knowledge, including secret information, to maintain the existing order (Brahmanical) but also in morally appropriate action (Gray, 2014). For example, a conquering state would have to exercise leniency and tolerance towards the subjects of the enemy state in order to fulfil God’s will for self- and foreign-development and moral perfection (Shahi, 2019: 34).

In Thomas Aquinas, mental self-orientation competence analytically breaks down into three stages of action: inner deliberation (*consiliari*), selection among possible courses of action (*iudicare)*, and execution of the most reasonable option (*praecipere*). However, unlike Aristotle and comparable to Kautilya, prudence (*prudentia*) does not primarily aim at the acting individual, but at the *bonum commune*, the order given by God (Horn, 2005). Nevertheless, in addition to the virtue of the monarch, which shows itself in the *ars legislativa*, the *ars economica* and *ars militaris* for the good of the community, the *prudentia politica* also knows the ordinary citizen as a bearer of political prudence, which, in turn, shows itself in loyalty, public spirit and willingness to work for the community (Horn, 2005: 64).

Turning to comparative history of the concept enables one to expose the distortions about political prudence in Niccolo Macchiavelli’s work. It has often been argued that Macchiavelli’s writing ‘Il principe’ aims at recommending to the ruler a prudence based on the preservation of power and coercion and deception without morality, which makes the preservation of the state alone the highest good of political prudence (reason of state). As Otfried Höffe has convincingly pointed out (Höffe, 2005), though, Machiavelli is concerned with defending the republican state, which is committed to the welfare of its citizens. Since the prince must reckon with the deviousness of his opponent, he must not abandon the commonwealth by believing his opponent's assurances, but must make this deviousness the basis of his own actions (Höffe, 2005: 310).

As an analytical concept, political intelligence can therefore be understood as a relational concept that combines mental and affective processes of self-orientation over time (temporal relationality) with processes of self-orientation towards others (social relationality), especially in social groups and political communities. Steadiness towards oneself, i.e. ontological security (Giddens, 1991), and external reliability, i.e. reputation (Mercer, 2010), form important individual and social resources for the self-determined choice of politically relevant goals and strategies that can be attributed as authentic by other actors. Without empathy, the form of social relationality that attempts to anticipate the interests and wishes of others through identification with them, the consequences of one's own actions cannot be measured (Pedwell, 2014). If this self-other orientation competence is lacking, the intention of one's own action can be altered or even reversed in its effect by the action of the other, or the lack thereof.

Meanwhile, wisdom, especially political wisdom, arises when empathy with the self is strong over time (life wisdom), and the ability to empathize with others in the past, present and future leads third parties to identify with this wisdom over time, space and affect (transversal wisdom). Social and emotional intelligence are also important components of any political intelligence because, in addition to satisfying cognitive and emotional needs, they are also able to address or employ the physical and spiritual needs of individuals in communities (cf. Funke, 2021).

Here, I want to highlight three implications of this relational concept of political intelligence: First, intelligence occurs whenever agency—the ability to determine goals for action and to select from a set of alternative options the one that seems most appropriate after weighing the respective consequences—encounters a concrete problematic situation. Actors may have appropriate cognitive, emotional or social resources at their disposal without ever applying them, and communities may solve political problems even without political intelligence being present. Political intelligence is therefore a special relation between individual or collective agency and social problem-solving. Second, political communities—or at least their identifiable precursors—can exist even if they do not have independent mechanisms or agency that promise solutions. If, for example, members of an ethnic, socio-cultural or political group are scattered across different states, political intelligence may be needed to unite them (peacefully). Finally, political intelligence may be used to exploit or manipulate a community, although this type of asymmetric solution-competence relationship is by no means a natural consequence of political intelligence. However, the reciprocal and asymmetrical condition of particular agency and community problem-solving explains why political intelligence is often used pejoratively, in the sense of the deviousness, disloyalty or imperiousness of political decision-makers.

Intelligence can therefore result in very different relational forms of political order: Autocracy legitimized or stabilized by force and coercion, the skilful economic or political co-optation of minorities and majorities, or the voluntary consent of those subject to rule. Charismatic rule, politically or religiously motivated, is thereby often based on the continuing ascription of special individual abilities and powers that are of an eternal – i.e., in the respective cultural context, supra-temporal – nature. It requires special forms of political intelligence to make charismatic rule by individuals or groups permanent or to supplement or replace it with other forms of rule.

The rule of the many, however, often only permits such forms of political intelligence that provide for a uniform distribution of political intelligence in the sense of moderation, community or future orientation between those empowered to rule and those subjected to rule. Populist rule, often accompanied by the notion that a unified and blameless body of the people must be protected against established elites, regularly destabilizes the democratic fabric of authority. The population is assumed to lack self-determination competence so that a need for charismatic leadership arises. First temporarily and then permanently, the existing institutional barriers to autocratic rule are disregarded and abolished.

Market economy's focus on finance together with neocolonialism may produce new forms of political domination by creating economic dependencies through the particular functioning of markets, which bind the subjects of domination economically in perpetuity (Merkel, 2019). In this form, political intelligence enters a distinct economic logic as ruling groups anticipate the needs of the ruled, such as consumer goods, thereby perpetuating dependency relations and vice versa. For some, this is a purposeful and manipulative use of political intelligence to the detriment of the many; for others, it is the unintended consequence of the coaction of rulers and ruled; political intelligence, especially in this particular form, remains a contested concept (Gallie, 1956).

2 Theories of International Relations and Political Intelligence

Major theories of international relations are useful examples to illustrate different forms of political intelligence. Political intelligence can be understood as a special constellation of relations between individual or collective actors and social problems, the construction and maintenance of which regularly results from practices that are directed towards two properties: on the one hand, being able to select the quantity and quality of decision-making competence between alternative options for action in a goal-oriented manner; on the other hand, being able to identify the type and form of political problem constellations that require a solution. The logic, mechanisms and implications of these characteristics, i.e. how exactly decision-making competence is acquired and to which problems it is directed, can vary considerably. Positivist theories of international relations, realism and rationalism, assume that problem constellations can be identified objectively and unequivocally, while cognitivist and social constructivist approaches emphasize the intersubjectivity and ambiguity of problem perception. If, however, data about problem constellations speak for themselves, as realist and rationalist theorists assume, then their goal-directed processing is relatively simple for actors: the focus of intelligent solutions is then not on how to interpret the data, but on what data are available and what goal-means constellations can be derived from them.

Realist theories of international relations focus on the uncertainty resulting from the anarchic environment of states (or even between rival intra-state actors) and what possibilities for exploitation by another actor/state result (Waltz, 1979: 105; Mearsheimer, 1994: 10). Fear, conceived as the psychological disposition to believe that a negative consequence of action and its costs are more likely, is therefore the defining affect of actors in realism. This fear makes particularly sensitive to information about aggressive behaviour, while benign behaviour is barely perceived (Walt, 1987). And even when states do send out trustworthy signals-in the language of the theory, 'costly signals'- these signals cannot be trusted (Copeland, 2000: 22).

No matter how much information of what quality is available, because states can never know the future intentions of other states, their main focus must be on the capabilities—the physical power resources—that other states will have at their disposal to implement potentially malign intentions (Glaser, 1994: 56; Grieco, 1988: 500). Experiential knowledge, i.e. the link between one's own and others' intentions in situations with different resource allocations, recedes in this perspective, while the recognition of 'objective regularities' of power comes to the fore. It is not the determination of an actor, but its (military) capabilities, conditioned by geographical (including proximity, topography) and technological factors (superiority of defensive and offensive weapon systems) that determine the type and extent of targeted behaviour, deterrence or attack (Taliaferro, 2000/2001).

According to Hans Morgenthau, political prudence then arises from the statesman's ethical responsibility towards his own state and its citizens in the face of existential uncertainty. If the consequences of one's actions are uncertain, but the potential costs are high, there is a danger of a 'tragic misjudgement' of one's own capabilities (Molloy, 2009: 95; Barkin, 2010: 116).

> There can be no political morality without prudence; that is, without consideration of the political consequences of seemingly moral action. Realism, then, considers prudence – the weighing of the consequences of alternative political associations – to be the supreme virtue in politics. Ethics in the abstract judges action by its conformity with the moral law; political ethics judges action by its political consequences. (Morgenthau, 1978: 10–11).

In contrast to this ethically motivated position, Paul, in his monograph on the pursuit of nuclear weapons by states, advocates a structure-based perspective of 'prudential realism'. According to this perspective, under certain power–political conditions states would be in a position to refrain from accumulating military capabilities because these could be seen as threatening by other states (Paul, 2000: 5): States in zones of low to moderate threat would thus be prepared to forego the pursuit of nuclear weapons, because their cost calculations would have to be based on probabilistic rather than worst-case scenarios. Only in zones with an intense security dilemma is the pursuit of nuclear weapons by minor or middle powers likely—and their subsequent abandonment—unlikely (Paul, 2000: 24).

Political prudence, then, in classical realism, is defined by the limited extent of decision-making competence and the nature of the problematic constellation of actions. Intelligent agency is therefore limited to the prudent, i.e. restrained, management of one's own affects, which are characterized by fear of the unforeseeable intentions of other actors and the unforeseeable consequences of one's own actions. If, however, the opportunity arises to decisively expand one's own power potential through deception about one's own capabilities and/or early action in the face of changing power relations, then taking advantage at the expense of the other (relative profit-seeking) is most likely (Powell, 1991).

Rationalist theorists are no less sceptical about the uncertainties of international politics than representatives of the realist tradition. However, they assess the chances to be able to understand the intentions of other actors better and thus also to anticipate the consequences of one's own actions by means of information as significantly greater. Reality speaks for itself, as it were, but not all data are known. Agnostic ignorance, rather than anxiety or fear, therefore shapes the disposition of actors to act under rationalism (Rathbun, 2007: 542). States, i.e. the decision-makers representing them, therefore spend considerable time gathering and repeatedly assessing any information about the behaviour of other actors. By constantly adapting their capabilities and instruments to the changing (improved) information situation about the intentions and capabilities of other actors, states are able to learn from experience and thus achieve their goals more effectively and efficiently (Morrow, 1994: 163).

The (a-)symmetrical distribution of information, in particular information about the preference intensity of an actor, thus becomes the primary impetus of international politics and the skilful disclosure or concealment of information the instrument of intelligent politics. In order to reveal their intentions, states can send so-called 'costly signals' in disputes and negotiations that reveal their willingness to accept only certain outcomes (Fearon, 1997).

In rationalist approaches, intelligent policy is therefore primarily characterized by changing the cost of decisions through ties to domestic and/or international institutions. Thus, the merger of the European coal and steel industries in the ECSC[1] (also) signalled the willingness to abandon an autonomous rearmament policy by ECSC member states. By establishing independent central banks, governments regularly signal their willingness to maintain low inflation rates vis-à-vis financial market players, among others (Goodman, 1992). By enabling states to communicate their intentions for action effectively through forward-looking institution building, cooperation thus becomes possible in all those situations that were previously negated by realists through the assumption of exploitative behaviour (Kydd, 2005).

[1] European Coal and Steel Community (predecessor organisation of the European Communities and the European Union).

Skillful disclosure of information about one's own intentions can therefore enable weaker states to assert themselves is-à-vis stronger states in conflicts or negotiations if they can credibly demonstrate that they are extremely committed to a particular policy goal, e.g. that they cannot be expected to bow to threats of sanctions (Bueno de Mesquita et al., 1997). If the ratification of international treaties, as in the US, or of European treaties, as in the Federal Republic of Germany, is subject to the domestic ratification requirement of a two-thirds majority (amending the constitution), the respective contracting parties can be certain that even in the case of changing majorities the respective government will continue to comply with the treaty obligations of the predecessor government.

While domestic institutions (transparency, rule of law, ratification requirements, etc.) signal the willingness to commit oneself and to control affects, international institutions allow both the sharing of reliable information about norm compliance, the linking of mutual commitments across policy fields and longer time periods, and the (independent) sanctioning of misconduct (Abbott & Snidal, 1998). Intelligent policy solutions thus emerge in rationalism when actors, through institutions, shape the scope and nature of information in such a way that horizons of expectations for cooperative behaviour can emerge. Therefore, if a government attempts to conceal the negative consequences of an unpopular policy from its own population, as in the case of the Pentagon Papers, then rules about impunity for so-called whistleblowers can ensure that this information becomes available to voters (Becker, 2021). Following the liberal strand of rationalism, 'smart power' emerges from the growing participation of citizens and civil society groups in 'internationalizing politics' that takes into account the needs of interacting societies (Czempiel, 1999).

Compared to realists, and rationalists, who link their concepts of intelligence to the structure of the problem (power or information asymmetries), cognitivists and social constructivist theorists base their models of intelligence on the ambiguity of information for the acting decision-makers. Compared to rationalists, protagonists of cognitive approaches are not so much concerned with the distribution or nature of information about the world—the latter is taken as objectively given. The problem is rather the complexity of information about the world, which overburdens limited cognitive resources and therefore always allows only a limited perception of reality (Goldgeier & Tetlock, 2001). The ability to select the 'best solution' between alternative options is made more difficult in several ways, because on the one hand, decision-makers often differ in their perception of a problem and collective decisions can be influenced by individual stress and social group pressures, especially in crisis situations (Levy, 2013). On the other hand, the consequences of one's own actions have grown considerably due to the expansion of the tasks of states and the interdependence of actions between different policy fields, so that the weighing of goals between rival goods and values of one's own person or group is becoming increasingly difficult (Haas, 1980).

In order to reduce cognitive and emotional confusion, decision-makers therefore use a range of coping strategies, cognitive heuristics and emotional protective mechanisms (Jervis, 1976). Historical analogies, metaphors or foreign policy mental images can help make important decisions (Petersen, 2015). However, these coping heuristics are often subject to serious limitations and distortions: the tendency to weight losses more heavily than gains (Prospect Theory), to attribute the behaviour of other actors more to their intentions than to circumstances (fundamental attribution error), or to apply one's own heuristics indiscriminately to all problem constellations (overgeneralization) and to suppress deviating (negative) information (selective exposure) (Rapport, 2018).

In order to escape the cognitive limitations of individuals and decision-making groups, cognitive theorists therefore propagate solutions that aim to systematically promote knowledge—i.e. information about cause–effect relationships in specific situations—and to introduce it to the policy process in a targeted manner: on the one hand, they call for intensifying the exchange between expert scientists and decision-makers to reduce the tendency of decision-makers to adhere to existing heuristics despite negative experiences by systematically comparing different courses of action in similar problem constellations (Maliniak et al., 2020); on the other hand, (emotional) effects of peer pressure should be reduced by applying the devil's advocat techniques so that individual and collective needs for social confirmation do not turn into cognitive biases (George & Stern, 2002).

Political intelligence, in the cognitivist paradigm, thus emerges when individuals and collectives self-reflectively recognize the limitations of their cognitive abilities and seek to overcome them through creative solutions, such as the deliberate promotion of divergent perspectives. Expertise, e.g. mediated by international organizations or epistemic communities (Haas, 1990), is 'intelligent power' from this perspective, because it allows challenging the bias of existing heuristics and collective beliefs.

At the heart of social constructivist perspectives on political intelligence is the intersubjectivity of knowledge about the world (Harnisch, 2017). While most theorists assume that a material environment exists, its meaning can only be experienced through intersubjective processes of linguistic or practical ascription of meaning. Uncertainty about another actor's intentions and capabilities is therefore an indeterminacy until it has been placed in a hostile, rival or friendly relational context through language and action (Wendt, 1999).

The social constructivist understanding of uncertainty as indeterminacy thus de facto subsumes the realist understanding of uncertainty as fear and the rationalist understanding of uncertainty as ignorance (Rathbun, 2007: 550). From this perspective, because human individuals and collectives have the capacity for self-reflection, they also fundamentally have the capacity to 're-understand' their environment. This 'transformative ontology' of social constructivism (Dessler, 1989) alters the conception of political intelligence in several ways because, depending on the cultural and temporal context, it is first 'made' by actors. To paraphrase an oft-cited aperçu of Alexander Wendt (1992): 'Political intelligence is what actors make of it'.

In social constructivism, the distribution of information in rationalism as well as the distribution of knowledge in cognitivism becomes the affect-occupied certainty about the 'self', i.e. ontological certainty (Mitzen, 2006), and the world. The co-emergence of affect-occupied actor identities—relatively stable self-attributions over time—and norms—standards of appropriate behaviour in a group—is therefore at the heart of change in the ascription of meaning in international politics. This change can occur through socialization processes—the (voluntary) appropriation of existing group norms by a new member—or persuasion processes—the intersubjective linking of new knowledge with existing norms and values—by individuals, so-called norm entrepreneurs (Finnemore & Sikkink, 1998) or collective actors, e.g. international organizations (Finnemore & Barnett, 2004). Learning in this perspective is thus the intersubjective reconstruction of reality—including the identities and roles of the actors—and not only the better understanding of the (objective) 'causal forces' that prevail in it (Harnisch, 2012).

By linking processes of social meaning change with affect-occupied identity changes, social and emotional intelligence becomes the object of the social constructivist conception of intelligence. For states can only superficially accept norms in order to benefit from the corresponding recognition as legitimate members of a community of states (constitutive effect of the norm) without accepting the duties arising from the norm (regulative effect of the norm). States therefore regularly attempt to publicly (or privately) shame states that violate norms (naming and shaming), in the assumption that the withdrawal of social recognition and questioning of an actor's credibility (loss of reputation) could promote compliance with the norm. Meanwhile, if shaming undermines the domestic legitimacy of a government or the identity of individual decision-makers, it may result in defiance and/or even withdrawal from the norm community (Snyder, 2020). Against this background, intelligent politics could consist of asking whether public shaming should primarily serve the self-assurance and legitimation of the shamer, no matter what consequences this has on the behaviour of the shamed; or whether and how the shaming, as for example in the case of human rights violations against the Uyghur minority by the Chinese government, should be formulated so that the shamed actor can change their behaviour without losing their identity and legitimacy (Gallagher, 2021).

Intelligent politics thus arises when political actors in a problem constellation of indeterminacy arrive at an 'appropriate solution' through reflected processes of self-assurance—who am I in this situation and what constitutes this situation—and assignment of meaning: This solution can aim at maintaining the existing norms and identities—status quo—or at revising them.

3 The End of Political Intelligence?

The end of the East–West conflict and the establishment of democratic and (neoliberal) market economy norms were the two most significant developments in international politics at the end of the twentieth century. At the beginning of the twenty-first century, human rights and free-market principles have spread widely, starting from the Western community of states. The formation of alternative alliances of states, the open breach of sovereignty and human rights by Russia and China, the failure of US-led liberal interventions in Afghanistan, Iraq and Libya, the rollback of democratic rules and norms in many democracies, and the rise of populist parties and governments in many democracies illustrate that liberal conceptions of reason based on the dignity of every human being, separation of powers and the rule of law are challenged.

This acceleration of political time goes hand in hand with rapid, technology-driven, social and economic change, resulting in a 'broad present' (Gumbrecht, 2010) that simultaneously incorporates more and more of the past and promises to regulate the future, e.g. anthropogenic climate change. Political intelligence, at least in pluralistic societies, must therefore accommodate this new complexity by becoming simultaneously more multidimensional and more balanced: In the face of a pandemic of global proportions, liberty, property and patent rights should be reconciled differently with basic human rights to physical integrity than would be the case under 'other circumstances'. Under conditions of potentially accelerating anthropogenic climate change, constitutional courts may have to interpret judicial self-restraint more courageously when elected representatives primarily represent the present demos but do not sufficiently consider the interests of the future demos and thus the continuation of the polity. Under conditions of growing individual and collective claims to development in the present, their systematic disregard in the past, often reverberating through language and institutions to this day, cannot go unspoken because this 'simultaneity of the non-simultaneous' limits the range of intelligent solutions for the present and future. Intelligent forgetting should be a mutual and voluntary one, and not one based on an octroy (Meier, 2010). While old and new forms of political intelligence are increasingly questioned, politics, science and society must therefore search for alternative forms of reflective self-orientation in order to find 'appropriate solutions' in each case.

References

Abbott, K. W., & Snidal, D. (1998). Why states act through formal international organizations. *Journal of Conflict Resolution, 42*(1), 3–32.

Barkin, J. S. (2010). *Realist constructivism: Rethinking international relations theory*. Cambridge University Press.

Becker, E. (2021). The secrets and lies of the Vietnam war, exposed in one epic document. *New York Times*. Retrieved June 9, 2021, from https://www.nytimes.com/2021/06/09/us/pentagon-papers-vietnam-war.html?smid=url-share

Bueno de Mesquita, B., Morrow, J. D., & Zorrick, E. R. (1997). Capabilities, perception, and escalation. *American Political Science Review, 91*(1), 15–27.

Copeland, D. (2000). *The origins of major war*. Cornell University Press.

Corcilius, K. (2021). Phronesis/practical wisdom. In C. Rapp & K. Corcilius (Eds.), *Aristoteles-Handbuch* (pp. 351–359). J.B. Metzler. https://doi.org/10.1007/978-3-476-05742-6_54

Czempiel, E. O. (1999). *Smart power. Foreign policy for the 21st century*.

Dessler, D. (1989). What's at stake in the agent-structure debate? *International Organization, 43*(3), 441–473.

Draguhn, A. (2021). Intelligent brains—the physiology of intelligence. In R. M. Holm-Hadulla, J. Funke, & M. Wink (Eds.), *Intelligence*. Heidelberg University Press. (in this volume).

Fearon, J. D. (1997). Signaling foreign policy interests: Tying hands versus sinking costs. *The Journal of Conflict Resolution, 41*(1), 68–90.

Finnemore, Martha/ Barnett, Michael (2004). Rules for the world: International organizations in global politics. Cornell University Press.

Finnemore, Martha/Sikkink, Kathryn (1998). International norm dynamics and political change. International Organization 52(4): 887–917.

Funke, J. (2021). The psychology of intelligence. In R. M. Holm-Hadulla, J. Funke, & M. Wink (Eds.), *Intelligence*. Heidelberg University Press. (in this volume).

Gallagher, A. (2021). To name and shame or not, and if so, how? A pragmatic analysis of naming and shaming the Chinese Government over mass atrocity v crimes against the Uyghurs and other Muslim Minorities in Xinjiang. *Journal of Global Security Studies*. https://doi.org/10.1093/jogss/ogab013

Gallie, W. B. (1956). Essentially contested concepts. *Proceedings of the Aristotelian Society, 56*, 167–198.

George, Alexander L./Stern, Eric K. (2002). Harnessing conflict in foreign policy making: From Devil's to multiple advocacy. Presidential Studies Quarterly, 32: 484–505.

Giddens, A. (1991). *Modernity and self-identity: Self and Society in the Late Modern age*. Stanford University Press.

Glaser, C. L. (1994). Realists as optimists: Cooperation as self-help. *International Security, 19*(3), 50–90.

Goldgeier, J. M., & Tetlock, P. E. (2001). Psychology and international relations theory. *Annual Review of Political Science, 4*, 67–92.

Goodman, J. B. (1992). *Monetary sovereignty: The politics of central banking in Western Europe*. Cornell University Press.

Gray, S. (2014). Reexamining Kautilya and Machiavelli: Flexibility and the problem of legitimacy in Brahmanical and secular realism. *Political Theory, 42*(6), 635–657.

Grieco, J. M. (1988). Anarchy and the limits of cooperation: A realist critique of the newest Liberal institutionalism. *International Organization, 42*(3), 485–507.

Gumbrecht, H. U. (2010). *Unsere breite Gegenwart*. Suhrkamp.

Haas, E. B. (1980). Why collaborate: Issue-linkage and international regimes. *World Politics, 32*(3), 357–405.

Haas, E. B. (1990). *When knowledge is power: Three models of change in international organizations*. University of California Press.

Harnisch, S. (2012). Conceptualizing in the minefield: Role theory and foreign policy learning. *Foreign Policy Analysis, 8*(1), 47–71.

Harnisch, Sebastian (2017). Social constructivism in international relations, in: Masala, Carlo/ Sauer, Frank (eds.): Handbuch Internationale Beziehungen. 2nd Springer VS, 215–232.

Höffe, O. (2005). Klugheit im politischen Projekt der Moderne. In W. Kersting (Ed.), *Klugheit* (pp. 301–317). Wissenschaftliche Buchgesellschaft.

Horn, C. (2005). Klugheit bei Thomas von Aquin. In W. Kersting (Ed.), *Klugheit* (pp. 42–67). Wissenschaftliche Buchgesellschaft.

Jervis, R. (1976). *Perception and misperception in international politics*. Princeton University Press.

Kersting, W. (Ed.). (2005a). *Klugheit*. Wissenschaftliche Buchgesellschaft.

Kersting, W. (2005b). Der einsichtige Staatsmann und der kluge Bürger, Praktische Vernünftigkeit bei Platon und Aristoteles. In W. Kersting (Ed.), *Klugheit* (Vol. 2005, pp. 15–42).

Kydd, A. (2005). *Trust and mistrust in international relations*. Princeton University Press.

Levy, J. S. (2013). Psychology and foreign policy decision-making. In L. Huddy, D. O. Sears, & J. S. Levy (Eds.), *The Oxford handbook of political psychology* (2nd ed., pp. 301–333). Oxford University Press.

Maliniak, D., et al. (Eds.). (2020). *Bridging the theory-practice divide in international relations*. Georgetown University Press.

McCourt, D. (2012). Phronesis and foreign policy in theory and practice. *E-International Relations*. Retrieved November 23, 2012, from http://www.e-ir.info/2012/11/23/phronesis-andforeign-policy-in-theory-and-practice/

Mearsheimer, J. J. (1994). The false promise of international institutions. *International Security, 19*(3), 5–49.

Meier, C. (2010). *The imperative to forget and the irrefutability of remembering. On the public treatment of the bad past*. Siedler Verlag.

Mercer, J. (2010). *Reputation & international politics*. Cornell University Press.

Merkel, W. (2019). Aus dem Gleichgewicht. *Die Zeit*. Retrieved June 17, 2019, from https://www.zeit.de/wirtschaft/2019-04/kapitalismus-finanzialisierung-globalisierungdemokratie-ungleichheit

Mitra, S., & Liebig, M. (2016). *Kautilya's Arthashastra: An intellectual portrait. The classical roots of modern politics in India*. Nomos.

Mitzen, J. (2006). Ontological security in world politics: State identity and the security dilemma. *European Journal of International Relations, 12*(3), 341–370.

Molloy, S. (2009). Hans J. Morgenthau versus E. H. Carr: Conflicting conceptions of ethics in realism. In D. Bell (Ed.), *Political thought and international relations* (pp. 83–104). Oxford University Press.

Morgenthau, H. (1978). *Politics among nations* (5th ed.). Knopf.

Morrow, J. (1994). *Game theory for political scientists*. Princeton University Press.

Paul, T. V. (2000). *Power versus prudence why nations forego nuclear weapons*. McGill-Queen's University Press.

Pedwell, C. (2014). *Affective relations. The Transnational Politics of Empathy*. Palgrave Macmillan.

Petersen, M. B. (2015). Evolutionary political psychology: On the origin and structure of heuristics and biases in politics. *Advances in Political Psychology, 36*, 45–78.

Powell, R. (1991). Absolute and relative gains in international relations theory. *American Political Science Review, 85*(4), 1303–1320.

Rapport, A. (2018). Cognitive approaches to foreign policy analysis. In C. Thies (Ed.), *Oxford encyclopedia of foreign policy analysis* (Vol. 1, pp. 167–185). Oxford University Press.

Rathbun, B. C. (2007). Uncertain about uncertainty: Understanding the multiple meanings of a crucial concept in international relations theory. *International Studies Quarterly, 51*(3), 533–557. https://doi.org/10.1111/j.1468-2478.2007.00463.x

Shahi, D. (2019). *Kautilya and non-Western IR theory*. Palgrave Macmillan.

Snyder, J. (2020). Backlash against naming and shaming: The politics of status and emotion. *The British Journal of Politics and International Relations, 22*(4), 644–653.

Sternberger, D. (1997). The word 'Politics' and the concept of the political. In W. Seibel, M. Medick-Krakau, H. Münkler, & M. T. Greven (Eds.), *Democratic politics—Analysis and theory* (pp. 97–105). Political Science in the Federal Republic of Germany. Politische Vierteljahresschrift—Sonderheft.

Taliaferro, J. W. (2000/2001). Security seeking under anarchy: Defensive realism revisited. *International Security 25*(3):128–161.

Walt, S. (1987). *Origins of alliances*. Cornell University Press.

Waltz, K. (1979). *Theory of international politics*. Random House.

Wendt, A. (1992). Anarchy is what states make of it: The social construction of power politics. *International Organization, 46*(2), 391–425.

Wendt, A. (1999). *Social theory of international politics*. Cambridge University Press.

Sebastian Harnisch is Professor of International Relations and Foreign Policy at Heidelberg University, a member of the Board of Directors of the Heidelberg Center for American Studies (HCA), and was a long-time board member of the Heidelberg Center for the Environment (HCE). His research projects and publications cover the areas of comparative foreign and security policy, theories of international relations, non-proliferation, network policy and climate change and have been funded by the German Research Foundation (DFG), the German Foundation for Peace Research (DSF), the Fritz Thyssen Foundation and the Korea Foundation, among others.

In the course of his academic career, he has taught at the University of Trier, the University of the Federal Armed Forces Munich, Beijing Foreign Studies University, Al-Farabi National Kazakh University and China Foreign Affairs University. He has been a visiting scholar at Columbia University in New York, Yonsei University in Seoul, and the Japan Center for International Exchange in Tokyo. In 2012–2013, he was a Research Fellow at the Marsilius-Kolleg Heidelberg.

Sebastian Harnisch is a member of the Scientific Advisory Board of the journal *Foreign Policy Analysis and* co-editor of the series *Foreign Policy and International Order* (Nomos Verlag) and *Oxford Research Encyclopedia for Foreign Policy Analysis* (Oxford University Press). He has published numerous monographs, edited volumes and research articles in renowned journals.

Index

R. M. Holm-Hadulla et al. (eds.), *Intelligence - Theories and Applications*,
https://doi.org/10.1007/978-3-031-04198-3

T

U

V