MARKUS KNAUFF

SPACE TO REASON

A SPATIAL THEORY OF HUMAN THOUGHT

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To the memory of my mother

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Preface

This book is about imagination! And it is about logic! Two things that do not fit together? Imagination is often seen as something mysterious, and an Internet search brings you right away to quite esoteric pages or to scurrilous advertisements of miracle healers. Logic, on the contrary, is the epitome of rationality. Emotions are often considered to be a good thing, but logic is cold and an inhuman and heartless business.

My goal in this book is to provide a fresh and more *rational* view of the role of imagination in human logical reasoning. My first intention is to show that the concepts of imagination and logic share a long past and that the scientific studies of both have much to do with each other. My second motivation is to resolve some misconceptions about the role of visual mental imagery in human thought. One way to think about mental imagery follows from people's common report of experiencing their thinking as "seeing with their inner eye" or as having a "picturelike experience" in their head. Another way to think about it goes beyond the introspective and subjective experience (which almost nobody would deny) and defines visual imagery as something "real" in our brains that plays an essential role in our mental life. From this perspective, visual images are a special form of mental representation, characterized as similar to representations that come to mind as a result of the actual stimulation of the retina. The only difference from actual retinal images is that mental visual images are generated from memory or as the result of a process of thought. So do such visual images play a functional role in human logical reasoning? Or, to put it differently, does imagination play a crucial role in human rationality? Do we *need* visual mental images to draw inferences, to reason accurately and without error? For many scholars, the answer to this question is yes. Led by the influential work of Stephen Kosslyn, these researchers would agree that "it is clear that imagery plays a key role in reasoning" (Kosslyn, 1994, p. 404). However, my answer to the question is "(probably) not." Why? In this book, I first reexamine the imagery theory of human reasoning and try to resolve some apparent misconceptions about the visual character of reasoning. Second, I reject the visual theory of reasoning, and third, suggest an alternative theory of reasoning in its stead. My claim is that

1. visual images are *not* the basis of reasoning;
2. visual images can even *impede* the process of inference;
3. *supramodal* spatial representations are the basis of reasoning.

Based on these claims, I propose a *spatial theory of human reasoning* that relies on *spatial layout models*. My core idea involves drawing a clear contrast between visual images and spatial representations in reasoning, and showing that only spatial representations and processes are critical for reasoning. My proposal does not rely on visual images but explains why we often have the feeling that we think with our "mind's eye." However, my proposal is also not a purely propositional account, representing just the meaning of a picture in a language-like code, as Pylyshyn and other radical symbolists might hope. Instead I propose a *third way* to think about human reasoning that relies on supramodal spatial representations as being at the heart of human thought, even thought about nonspatial relations in the world. These spatial layout models are more abstract than visual images and more concrete than propositional representations. I report the empirical evidence supporting my space to reason theory in nine chapters.

Outline of the Book

Chapter 1 provides a brief historical introduction to the fields of reasoning and imagination, followed by a review of experimental findings on the kinds of mental representations that may be used in reasoning. Next, it summarizes the findings that established the distinction between visual and spatial representations in human cognition. Based on this review, I carefully distinguish between "inner eye" and "inner space" in human reasoning and explain the main background of my space to reason theory.

Chapter 2 introduces the main representational assumptions of the space to reason theory. I argue against the hypothesis that human reasoning is completely embedded in language and relies on formal rules of inference akin to those of formal logic. Instead I argue that reasoning requires going beyond language and is based on the construction, inspection, and variation of spatially organized mental representations. These representations are inherently spatial, more concrete than words, but more abstract than visual images. I refer to these spatial representations as spatial layout models and define the concept—following Marr's (1982) famous trichotomy—on the functional, algorithmic, and implementational levels of analysis. I show that the notion of spatial layout models results in clear predictions that can be tested experimentally.

Chapter 3 begins with an examination of previous studies of visual imagery and logical reasoning. It shows that there is indeed a confounding of materials that invoke visual imagery and materials that invoke spatial representations. Based on this review, I formulate the *visual impedance hypothesis*, which states that only spatial layout models are used in reasoning, whereas visual images without a spatial component relevant to inference can impede the process of reasoning. I then report a series of experiments that test this hypothesis. The experiments show that visual images are actually not critical for reasoning and may even retard the process.

Chapter 4 examines the relationship between reasoning and visuospatial working memory. It begins with a summary of the most important findings from the literature. Then I review studies in which the concept of resource limitation has been used to examine the role of visual and spatial representations in reasoning. The underlying idea of this experimental paradigm is that cognitive subsystems have limited capacities. Thus if concurrent tasks interfere with each other, then they share the same cognitive subsystem (e.g., a visual or spatial system). If not, they appear to be carried out in different systems. The results of these studies indicate that reasoning processes interfere with concurrent spatial tasks, but not with purely visual secondary tasks.

In chapter 5, I turn to studies on how the human brain processes visual and spatial information during reasoning. Brain imaging studies have provided evidence that the parietal cortex plays a key role in reasoning and thus support the idea that reasoning involves representations and processes of an abstract spatial nature. Yet these studies have also shown concurrent activation in vision-related cortical areas, which has been interpreted as evidence for the role of visual imagery in reasoning. The main claim of the chapter (supported by several experiments), however, is that visual brain areas are only involved if the problem information is easy to visualize. Reasoning in general, however, does not involve the construction of visual images. Instead it involves more abstract spatial representations held in parietal cortex. Only these spatial layout models are crucial for the genuine reasoning process.

Chapter 6 examines the problem of indeterminacy in human reasoning. A reasoning problem is indeterminate if its description is ambiguous and therefore interpretable in several different ways. To deal with this problem, I introduce the notion of *preferred layout models*. A preferred layout model is one specific spatial layout model among many others that has the best chance of being mentally constructed. Importantly, this model also preserves just spatial information without incorporating pictorial features that are normally presented in visual images. I show that preferred layout models, once constructed, guide the further process of inference, and alternative interpretations of the problem are mostly neglected. This leads to difficulties and invalid inferences.

Chapter 7 starts with an outline of literature on computational models of reasoning with visual and spatial information. Two specific computational models of reasoning with preferred layout models are compared. One model is based on visual images, the other on purely spatial representations. A comparison with data from human experiments supports the spatial theory of reasoning. Based on this comparison, I describe a general computational theory of reasoning with spatial layout models. The PRISM model (preferred inferences in reasoning with spatial mental models) maps spatial working memory to a symbolic spatial array and uses a spatial focus that places and manipulates tokens in the array. The PRISM model results in a complexity measure that helps us predict which spatial layout model is preferably constructed and why other models are neglected. A comparison with data from psychological experiments shows that the computer program can simulate human reasoning performance, including errors and preferences.

In chapter 8, I try to clarify why we so often have the impression of reasoning "before our mind's eye." I propose that, in the foreground, we indeed tend to envisage the scenario portrayed in a reasoning problem with a visual image (at least if the situation is easily visualizable), and it is therefore natural that people believe they use these mental pictures to think. In fact, however, I argue that such superimposing images are only present in the foreground of conscious experience, but behind the images, the actual logical work is carried out by reasoning-specific operations on abstract spatial layout models and additional executive control processes. This theory is by no means complete, so that this chapter is probably the most speculative of the book. Yet the main direction of this account seems to me to be on the right track for future research that explains the myth of thinking in pictures.

Chapter 9 summarizes the ideas presented in the book and draws some general conclusions about imagination, spatial representation, and reasoning. I also sketch some practical implications of the space to reason theory and then, more thoroughly, discuss how preferred layout models are related to the issue of human rationality. I close by concluding that the visual theory of reasoning might be too romantic and that a more rational view of imagination helps us develop a better understanding of what drives our thinking and reasoning. It is not the inner eye but the inner space that makes us (most of the time) as clever as we are. Finally, I explain what all of this has to do with the thoughts of a Neanderthal woman.

Acknowledgments

Space to Reason is based on work on visual and spatial processes in human reasoning that has been conducted in my lab during the last fifteen years. It relies on this experimental work but goes beyond it, putting the results into a broader context and suggesting a new theory of spatial representation in human reasoning. Some of the ideas have been published elsewhere, but this is the first time that I present and integrate all experimental findings and theoretical considerations in a single work. I thank all the publishers who granted the permission to reproduce parts of these materials here.

I have infected many doctoral and postdoctoral students, colleagues, and friends with the reasoning virus. Others were already experts in the field from whom I learned a lot. Yet others were from other fields and forced me to scrutinize my ideas more closely. I thank all of them for many inspiring discussions and for their help in all phases of the research reported here. Without their support, collaboration, and critical acumen, the research would not have been carried out so well or to such interesting and useful ends. I list all of them here in alphabetical order, because all of them have contributed in many different and indispensable ways to making this book a reality. So I am

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This book is a product of many inspiring environments at several institutions: the University of Freiburg (where portions of this work were part of my habilitation thesis), Princeton University (where I spent time as a visiting postdoctoral researcher), the Max Planck Institute for Biological Cybernetics (where I stayed as Heisenberg Scholar), the University of California, Santa Barbara (where I wrote the main parts of this book during a sabbatical), and the University of Gießen, which is now my home university and has an excellent and stimulating psychology department with a very research-friendly atmosphere. A special thanks also goes to the German Research Foundation (DFG), which has made this project possible. In 2003, the DFG awarded me a Heisenberg Fellowship that freed me for three years from other duties and allowed me to set up a research laboratory to study human reasoning. Later the DFG supported my research with several research grants, partly within the Interdisciplinary Transregional Collaborative Research Center Spatial Cognition (SFB/TR8) at the universities of Freiburg and Bremen. In the research center, I had the opportunity to work with many leading spatial cognition researchers in the fields of psychology, computer science, linguistics, and robotics. I express my sincere thanks to all of them. Finally, I thank Philip Laughlin, Katie Persons, Judith Feldmann, William Henry, and the staff of the MIT Press for helping me with all my concerns and for shepherding the book through the publication process.

1 Inner Eye and Inner Space

In philosophy, Kant, Leibniz, and Descartes, and in logic, George Boole and others, formed a picture of humans as intelligent creatures who think rationally and follow logical rules. In our daily life, however, we are often painfully aware that we are far from this self-delusion of rationality and logical reasoning. A robot in a science fiction movie or a professor of logic might follow the rules of formal logic, but normal people often make errors in logical reasoning and behave irrationally. People with superior logical abilities outperform other individuals in many problem areas of daily life; they are more successful, earn higher academic grades, get better jobs, and have more chances to live a satisfied and fulfilling life. Individuals with less logical competence are at a higher risk of making poor decisions and failing at the challenges of life.

This book is concerned with an aspect of logical thinking that has been at the heart of much disagreement in philosophy and psychology. Do people use visual mental images to reason? To get an intuitive feeling for this issue, try to solve the following problem:

The blue Porsche is parked to the left of the red Ferrari.
The red Ferrari is parked to the left of the green Beetle.

Is the blue Porsche parked to the left or to the right of the green Beetle?

If you ask people how they deal with such relational reasoning problems (I return to the structure of such logical problems later), they often report that they form a mental picture in their "inner eye" and then "look at" this picture to find new information that is not explicitly given in the problem description. For instance, a respondent will typically answer that he or she pictured the three cars in a parking lot and then "looked at" this mental picture to "see" the spatial relation between the blue Porsche and the green Beetle. But is this subjective experience of visual imagery related to the underlying "reality" of the mental representations and processes that are actually involved in solving the problem? Proponents of the theory of visual mental imagery do not doubt that the assumption is true: visual images are an important part of human cognition, and so it is natural to assume that they also play a key role in reasoning (e.g., Gattis & Holyoak, 1996; Gilbert, Reiner, & Nakhleh, 2008; Kosslyn, 1994; Kosslyn, Ganis, & Thompson, 2006; Johnson-Laird, 1998; Reed, 2010; Steiner, 1980). Other researchers are, on the whole, dismissive about the role of visualization in human thought. For these scholars, reasoning is solely based on propositional representations as a (formal) language of thought. Broadly speaking, a proposition is a mental entity that represents *meaning* in a language-like code. Propositions have a truth value, they are true or false, and they can be combined to capture the meaning of what is presented in a picture (and all other perceptual or emotional experiences). Although propositional representations should not be identified with linguistic representations, they are language-like in the sense that they comprise abstract symbols as a language does (Anderson, 1983, 1993). For proponents of the propositional theory of human cognition, headed by Zenon Pylyshyn, visual imagery is a mere epiphenomenon that does not play a causal role in our mental machinery (e.g., Adler & Rips, 2008; Pylyshyn, 1973, 2002, 2006; Rips, 1994).

Thinking in the Inner Eye?

Different opinions on the role of visual imagery in human thought have been with us since the early years of science and the humanities. Belief in the role of imagination was in part based on the introspective report of scientists, and some contemporary scholars even allege that vivid imagination was the key to unlocking the secrets of chemistry and physics in the nineteenth century (Robinson, 2010). One example is the famous Austrian physicist Ludwig Boltzmann, who claimed that all our ideas and concepts "are only internal pictures" (Boltzmann, 1890). Another example is the chemist Friedrich August Kekulé von Stradonitz, who reported that visualization had suggested to him that the benzene molecule might have a cyclic structure (Kekulé, 1865). Here is Kekulé's famous quote from 1865:

> I turned my chair to the fire and dozed. Again the atoms were gamboling before my eyes. This time the smaller groups kept modestly in the background. My mental eye, rendered more acute by the repeated visions of the kind, could now distinguish larger structures of manifold conformation; long rows sometimes more closely fitted together all twining and twisting in snake-like motion. But look! What was that? One of the snakes had seized hold of its own tail, and the form whirled mockingly before my eyes. As if by a flash of lightning I awoke; and

this time also I spent the rest of the night in working out the consequences of the hypothesis. (Cited in Japp, 1898, p. 138)

Similar assumptions were articulated in other areas, such as the arts. Rudolf Arnheim claimed in his unique classic *Visual Thinking* (1969) that visual imagery is the sufficient condition for artistic creation. For Arnheim, all artwork requires a highly differentiated capability of organizing the various components of a visual image in a comprehensive compositional order. One of the most impressive applications of the imagery concept comes from the architect and city planner Kevin Lynch, a student of Frank Lloyd Wright. In his book *The Image of the City* (1960), Lynch explored what a city planner can do to make the city's image more vivid and memorable to the city's residents and visitors. To answer these questions, Lynch formulated a new criterion—imageability—and showed its potential value as a guide for the building and rebuilding of cities.

In philosophy, we can trace the idea of thinking in the mind's eye back to early Greek philosophers—for example, Aristotle's term *phantasma*—as well as more modern philosophers like Descartes, Locke, and Hume. Although all these philosophers developed different thoughts about the structure and function of mental imagery, they all held that ideas are pictorial mental images (for detailed discussions of the imagery concept in philosophy, see Thomas, 2011; or Tye, 1991). To think *is* to visualize, so to say. However, other scholars and philosophers such as Ryle (1949) and notably the later Wittgenstein (1953/2001) denied the importance of pictorial mental images in cognition. Particularly for Wittgenstein, who expended much effort exploring the concept of mental imagery, the whole notion of images in the mind was rooted in deep philosophical misunderstandings (Wittgenstein, 1953/2001; Thomas, 2011).

Diverse opinions about the role of images in cognition were also reflected in the early years of scientific psychology. Overall, most pioneers of psychology, such as William Wundt, the founder of modern psychology, believed that mental images are an important part of human cognition and thus it would be natural to suppose that mental imagery helps us to reason (Wundt, 1896). However, during the early decades of the last century, a serious academic dispute took place in Germany and later among American psychologists about the role of visual images in human cognition. Although functions of the human sensory systems were still of great interest to these psychologists, a growing area of their attention was the role of visual imagery in thinking, reasoning, and problem solving. On the one hand, in 1910, Cheves Perky discovered that mental imagery can be phenomenologically indistinguishable from visual perception, and people can be shown to merge mental images and what is actually seen. In other words, visual imagery can be so similar to real perceptions that imagination can be mistaken for reality (Perky, 1910). On the other hand, the Würzburg school around Oswald Külpe, a former student of Wundt, promoted the idea that thinking is possible without imagination. By taking this position, Külpe shattered the long-lasting consensus that imagination is a vital part of mental life. His skepticism regarding the functional role of images in cognition was mirrored in the so-called *imageless thought debate*. It was further advocated in experiments by Karl Bühler, who asked participants, for instance, "Does a man have the right to marry the sister of his widow?" and afterward asked them what had happened in their mind. From these reports, Bühler (1909) concluded that thinking is possible without seeing in the mind's eye. However, other authors criticized the peculiarity of Bühler's problems. For a long time, most researchers believed that thinking calls for “imagination” in the literal sense—that is, the activity of envisaging objects and scenes in their absence (e.g., Titchener, 1909).

Later, in Western psychology, publications on mental imagery engendered much controversy. Cognitive psychologists avoided the concept of imagery, given the crushing criticism it had received from behaviorists who questioned its use by the German introspectionists at the turn of the century (Watson, 1913; cf. Barsalou, 1992). In contemporary psychology, however, various evidence supports the claim that visual imagery is a vital part of human cognition, including the famous studies of mental rotation and the mental scanning of images (cf. Kosslyn, 1980; Shepard & Cooper, 1982). Based on these and many other experimental findings, Stephen Kosslyn developed the first modern cognitive theory of visual mental imagery (Kosslyn, 1980). Later he published a book on the neural foundations of visual imagery (Kosslyn, 1994), which was one of the first monographs that created links between a cognitive function and its implementation in the human brain. Today countless (good and less good) publications explore the relationship between imagery and, for example, creative problem solving, suggesting that visualization facilitates innovative solutions (e.g., Antonietti, 1991; Denis, Logie, Cornoldo, de Vega, & Engelkamp, 2001; Suler & Riziello, 1987; Steiner, 1980; Reed, 2010) and even scientific learning (e.g., Gilbert, Reiner, & Nakhleh, 2008). Moreover, in the last few years, the visual imagery approach has been in a way expanded to the *embodied cognition approach*, which is even more wide-ranging. It claims that, in general, the mind is embodied, and thus cognitive processes must be grounded in perceptual, motoric, or emotional experience (for an overview, see de Vega, Glenberg, & Graesser, 2008). From this point of view, human thought is almost exclusively based on perceptual simulations and modality-specific representations (Barsalou, 2008, 2010).

The first attempt to study the role of imagination and visual representation in human logical reasoning dates back to the work of the German scholar G. Störring (1908). Störring's work is only rarely recognized by modern reasoning researchers, although he was concerned with questions that are still of interest to modern scholars. In the first sentence of his paper, Störring states that he asked himself what experimental psychological research can contribute to the solution of debates between logicians and philosophers. Then, in the more-than-130-page article, he describes a series of experiments in which he studied the logical abilities of volunteers under highly standardized conditions (in a darkened room, under precise time control, etc.). He explored reasoning with syllogisms and with spatial, temporal, and abstract relations. His main conclusion from the retrospective reports of his volunteers was that people often try solving inference problems by imagining the content of the problem in their mind's eye, and they try to bring the elements of the reasoning problem into a "mental linear order." Störring viewed this mental linear order as an internal representation that reflects the synthesis of the terms in the premises.

Another pioneering study of mental imagery and logical reasoning was carried out about sixty years after Störring's work by the American psychologists DeSoto, London, and Handel (1965), who also argued that reasoners represent the elements of an inference problem as a mental image and then "read off" the conclusion by inspecting the image. Following this initial work, many other scholars investigated the role of visualization in logical reasoning and performed many well-designed experiments. Huttenlocher (1968), for instance, also interpreted her findings to mean that reasoners imagine an analogous physical arrangement of objects so as to cope with logical reasoning problems. Other authors reported that reasoning is sensitive to the visual features of the presentation format (Fuchs, Goschke, & Gude, 1989) and that reasoning is easier with problems that are easy to envisage than with problems that are hard to envisage (e.g., Shaver, Pierson, & Lang, 1975; Clement & Falmagne, 1986).

Several other studies, however, did not support the connection between visual imagery and reasoning. For instance, if reasoning relies on visual imagination, then problems easy to visualize should be easier to solve than nonvisualizable problems (I will return to this point later). The earlier example with the easily visualizable cars, for instance, should be easier to solve than the following logically equivalent problem:

A is better than B.
B is better than C.
———————————
Is A better or worse than C?

Both this version of the problem and the version with cars use a single transitive relation (and its converse in the conclusion), and new information can be inferred immediately from what is already given. However, several researchers have varied the imageability (visualizability) of reasoning problems in just this way but have failed to detect any effect of imageability on reasoning. Johnson-Laird, Byrne, and Tabossi (1989), for instance, examined reasoning with three transitive relations that differed in imageability: equality of height, correspondence of location, and kinship relationship. They found no effect of imageability on reasoning accuracy and reasoning speed.

Newstead, Pollard, and Griggs (1986) reported a similar result, and Sternberg (1980) did not find any reliable correlation between scores on the imageability items of IQ tests and reasoning ability. Overall, these and many other studies (which I will report later) provide reasonable grounds to be skeptical about the role of visual imagery in human reasoning.

Visual and Spatial Mental Representations

When I started to get interested in the role of imaginal processes in reasoning, I soon got the impression that the apparent inconsistency in previous studies might have arisen from a confusion between problems that invoke *visual imagery* and problems that invoke *spatial representations*. The mistaken equalization of the two concepts and the obvious misunderstandings about the spatial nature of images still seem to me to be one of the main barriers in the psychology of reasoning and motivated me to search for a deeper understanding of the distinction between visual and spatial representation in human cognition. In the following paragraphs, I summarize the experimental evidence from different areas of the cognitive sciences that supports this distinction. Then I describe the consequences this mistaken equivalence of visual images and spatial representation has had for reasoning research. Based on this discussion, I propose a clear terminological distinction between visual images and spatial representations.

For most cognitive scientists, the distinction between visual and spatial information processing is related to the neurophysiological work by Ungerleider and Mishkin (1982). These authors performed lesion studies with monkeys and reported that visual and spatial information is processed in different pathways of the brain. From these studies onward, it became common to distinguish between two cortical pathways, called the "what" and "where" systems in the brain. According to Ungerleider and Mishkin (1982), the "what" pathway—basically located in the occipital and temporal cortices of the monkey's brain—is responsible for visual object identification, that is, for the processing of the visual properties of objects, such as shape, texture, and color. In contrast, the "where" pathway is responsible for recognizing where objects are in space, spatial awareness, and the guidance of actions in space (see also Milner & Goodale, 1995). In humans, a similar distinction has been shown in many investigations of brain-damaged patients (e.g., Luzzatti, Vecchi, Agazzi, Cesa-Bianchi, & Vergani, 1998; Newcombe, Ratcliff, & Damasio, 1987) and with functional brain-imaging techniques (e.g., Smith et al., 1995). An illustration of the two pathways in the human brain is given in figure 1.1. Further findings that bear out this dissociation are reported in chapter 5.

Strictly speaking, it is not right to trace the origin of the "what" versus "where" distinction back to Ungerleider and Mishkin, because about fifteen years earlier, the neurophysiologist Gerald Schneider (1969) published a similar finding from research on the brain of the golden hamster.[1] Moreover, neurophysiological—as well as neuropsychological—results are not the only evidence for the distinction between visual and spatial cognitive processes. Notably, the British psychologist L. R. Brooks (1967, 1968) was one of the first cognitive psychologists to emphasize the necessity of distinguishing between spatial and visual representations in memory. In a number of well-known experiments, Brooks used interference of a primary task by concurrent secondary tasks to determine the representational format underlying different cognitive processes. The main idea of such

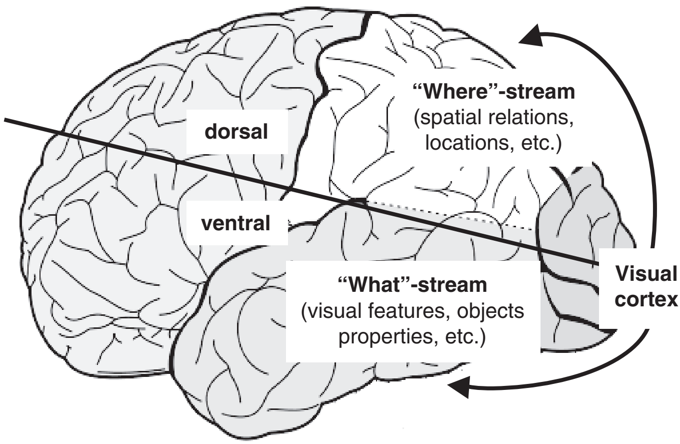

Figure 1.1
The ventral "what" and dorsal "where" pathways in the human cortex. The "what" pathway is concerned with visual properties of objects, such as shape, texture, and color; the "where" pathway is responsible for recognizing where objects are in space, spatial awareness, and the guidance of action in space.

experiments is the concept of resource limitation, which states that cognitive subsystems have limited capacities (Kahneman, 1973; Gopher & Donchin, 1986; Navon & Gopher, 1979). Thus, if tasks interfere with each other, then they share the same cognitive subsystem. If not, they appear to be carried out in different systems. In Brooks's studies, participants had to visualize a capital letter or numbers placed in a matrix at the same time that they performed a concurrent verbal or visuospatial task. Visualization was significantly poorer with the concurrent visuospatial task, whereas it did not suffer interference from the verbal task. Brooks interpreted these results to mean that the concurrent visuospatial task interfered with performance of the matrix visualization task because of its effects on subtasks, such as visual search or eye movement (Brooks, 1967, 1968). However, other researchers criticized this interpretation and pointed out a strong overlap between visual and spatial components in Brooks's tasks. Baddeley, Grant, Wight, and Thomson (1975) aimed at distinguishing both factors and used a secondary task in which participants had to follow a moving target as a purely spatial task. Tracking in these experiments had a significantly disruptive effect on the matrix task. Yet since a confounding of visual and spatial components also occurred in the tracking tasks, Baddeley and Lieberman (1980) performed a study in which the participants were blindfolded to remove any visual input. Participants had to follow a moving pendulum with a flashlight, and they were given auditory feedback about whether or not the light followed the pendulum accurately. Although the task involved no visual component, it disrupted performance in the matrix task, whereas purely visual tasks did not. Baddeley and Lieberman (1980) concluded that the system for visualization is spatially, rather than visually, organized. But this was not the end of the story. In fact, other researchers claimed that the results may have arisen from the spatial nature of the matrix task, and consequently replaced it with more visual tasks. Logie (1986) instructed participants to retain a series of words by means of the well-known peg-word memory technique, in which participants generate visual mental images and associate them with words to facilitate memory performance. This task—generally considered an extremely visual task—was combined with the concurrent presentation of irrelevant visual patterns. As predicted by the author, interference between visualization and additional visual input was measured.

These experiments represent only a few of the numerous studies showing that spatial memory tasks are disrupted by other spatial secondary tasks, but not by visual secondary tasks, whereas visual memory tasks are disrupted by visual secondary tasks, but not by spatial tasks. Several other groups have reported further results pointing in the same direction (Quinn, 1994; Quinn & McConnell, 1996, 1999; McConnell & Quinn, 2000; Logie & Pearson, 1997; for an overview, see Logie, 1995).

Another line of research explored the computational properties of visual and spatial information processing. Here an obvious question is whether the visual system is distinct from the spatial system, that is, if the two systems function cooperatively or independently. Rueckl, Cave, and Kosslyn (1989) compared different computational models to examine whether two systems processing visual and spatial information separately are advantageous to a single system. Simulations showed that the modular architecture with two specialized systems performed better than the nonmodular one with a single system that does not separate visual and spatial information. Thus, the authors hypothesized that modular architectures might be one of the reasons for the evolutionary emergence of the two distinct neural pathways (Rueckl, Cave, & Kosslyn, 1989). I will discuss other computational models in chapter 7.

Another classical work that speaks for the visual-spatial distinction is concerned with how human beings express visual and spatial information through language (Landau & Jackendoff, 1993). The main argument of these authors is that a nonlinguistic disparity between the representation of "what" and "where" is reflected in the representation of objects and places in language. Hence, the authors explored the language of objects and places and reported evidence that significant differences exist in the geometric richness with which objects and places are verbally encoded. The central finding is that for words referring to objects, detailed visual properties of the object are represented (especially its shape and axes), whereas for objects playing a role in locational expressions, only the object's main axes are primarily represented. In addition, these authors noted that the spatial relations encoded by spatial prepositions are nonmetric and relatively coarse, focusing in particular on topological, relative, and ordinal information. Landau and Jackendoff (1993) concluded that the words that describe what an object is are much more complex than those needed to describe where an object is. This approach was further developed by Bryant (1992), who argued that spatial representations can be built through perception or through language, but the mental spatial representations are the same in both cases. The evidence for this assumption comes from experiments indicating that individuals can construct accurate spatial representations of environments conveyed by verbal descriptions, and such representations preserve properties of space such as relative position (Bryant, Tversky, & Franklin, 1992; Franklin & Tversky, 1990; Mani & Johnson-Laird, 1982) and relative distances (Glenberg, Meyer, & Lindem, 1987; Morrow, Greenspan, & Bower, 1987; Rinck & Bower, 1995, 2000). A related concept is the "spatial image" developed by Loomis and Klatzky and collaborators (Klatzky, Marston, Giudice, Golledge, & Loomis, 2006; Loomis, Klatzky, Avraamides, Lippa, & Golledge, 2007).

A further line of research that bears out the visual-spatial dichotomy involves investigations with blind people. On the one hand, congenitally totally blind individuals—who do not experience visual mental images—should be impaired in reasoning with highly visual materials (e.g., Fraiberg, 1980). On the other hand, several studies show that persons who are blind from birth differ from sighted people in their use of visual images but are as good as the sighted in the construction of spatial representations (e.g., Kerr, 1983). In the last two decades, researchers have compared blind and sighted individuals performing a large variety of visual and spatial tasks, involving mental scanning, mental rotation, memory for paths and words, and so on (Marmor & Zaback, 1976; Zimler & Keenan, 1983). They have usually reported the same results: people who are blind from birth are able to envisage spatial arrangements but are unable to envisage visual mental images. Most explanations for these results rely on the distinction between the two different neural pathways associated with the processing of "what" and "where" information (Ungerleider & Mishkin, 1982). Vecchi (1998), for instance, conducted experiments with a dual-task paradigm involving participants who were blind from birth and reported that blind people's mental representations can rely on purely spatial information without a visual component. In a brain-imaging study (PET), Büchel, Price, Frackowiak, and Friston (1998) demonstrated that congenitally blind people show task-specific activation in spatial brain areas, whereas blind participants who lost their sight after puberty show additional activation in the primary visual cortex in the same task (Braille reading). All these studies show that persons who are blind from birth differ from sighted and late blind people in their use of visual images, but they are as good as the sighted and adventitiously blind in the construction of spatial representations (e.g., Kerr, 1983). A review of brain-imaging studies on visual cortex activity in early and late blind people can be found in Burton (2003).

Core Ideas of the Space to Reason Theory

The two main messages of the previous pages can be summarized as follows: First, the studies on the role of visual images in human reasoning leave us with a mixed and ambiguous picture. Some studies seem to support the role of images in reasoning, while many others do not. Second, the evidence strongly suggests that visual information and spatial information are processed differently and separately from each other. In the last two decades, almost all fields of the cognitive sciences have observed the visual-spatial dichotomy, ranging from low-level perception up to memory processes and the task of expressing spatial experience through language.

Based on these considerations, in this book, I aim to draw a clear contrast between visual and spatial representations in human thought, to reexamine the visual theory of reasoning, and to propose a spatial theory of reasoning in its stead. The theory that I suggest is distinctly different from any of its forebears in three essential aspects.

The first distinctive aspect is that the theory contributes a third way to approach the long-running debate on the role of mental imagery in human cognition (although I am unsure if both camps will be satisfied with my suggestion). The starting point of my proposal is that neither language-based propositional accounts nor theories of visual mental imagery alone are capable of explaining human reasoning. The third way that I suggest as part of my space to reason theory is that human reasoning is based on spatial representations that are more abstract than visual images and more concrete than propositional representations. In this account, I refer to a mental representation as a visual mental image if it is structurally similar to a real visual perception. It mentally represents the given visual information and, like a visual percept, represents colors, shapes, and metrical distances. Visual mental images can be scanned, have a limited resolution (cf. Kosslyn, 1980; Finke, 1989), and are sometimes so similar to real perceptions that the two can be confused (Johnson & Raye, 1981). Spatial representations, although they also integrate different types of information, avoid excessive visual detail and represent only information relevant to the inference. Unlike visual images, such representations can be spatial but more abstract in that they omit visual properties such as color or shape that may be irrelevant to the inference task at hand. Such a spatial representation is also able to depict nonspatial relations, such as “better/worse,” in a spatial way. While visual mental images represent information in a modality-specific visual format, spatial representations are not restricted to a certain representational format. They can capture the spatial information from different input modalities such as visual perception, hearing, touch, and language and represent the necessary information in a discrete, supramodal, or amodal representational format that maintains ordinal and topological properties and avoids irrelevant visual details. I call these spatial representations *spatial layout models*. Individuals might have no conscious access to these spatial representations, although they underlie our reasoning abilities. Or we experience spatial layout models as if they were visual images. However, what matters is not the subjective experience of the reasoner but rather what is actually processed by the cognitive system.

The second distinctive aspect of my approach is that it focuses not only on advantages but also on the *disadvantages* of visual imagery in human thought. In fact, most of the relevant literature is based on the assumption that visual images are generally functional in cognition and should thus have positive effects on human reasoning. Visualization is considered to be a good thing—by most scholars. I argue that this is not always true. In particular, I argue against the role of visual imagery in human reasoning and develop and test a provocative hypothesis that I call the *visual impedance hypothesis*. The hypothesis says that only spatial representations—spatial layout models—are used in reasoning, whereas visual images can impede the process of reasoning. My hypothesis is unique and challenges the orthodox visual imagery theory of reasoning. It is, I believe, also relevant to researchers in applied technology areas, such as artificial intelligence, human–computer interaction, information design, and multimedia learning. The main message for these disciplines is that visual images are often overrated and can actually be a nuisance for people's thinking. The hypothesis also argues against the excessive use of visual decoration, for instance in graph design, cartography, and multimedia learning (Mayer, 2009; Tufte, 2003).

The third distinctive aspect of my theory is that it strives to be both nonreductionistic and nonmentalistic at the same time. In the last decade, our group and a small number of other psychological laboratories have started to systematically investigate the connection between logical reasoning and the brain (for overviews, see Goel, 2007; Knauff, 2007; Prado, Chadha, & Booth, 2011). Before that, most reasoning researchers were committed to the assumption that human reasoning should be studied solely in terms of computational processes. The neural implementation of these computations was considered irrelevant, because any computational function can be computed on any hardware that is equivalent to a Turing machine, and thus also the brain (e.g., Newell, 1980; Pylyshyn, 1984). It has been widely recognized that neurophysiological substrates provide the biological basis of the mind, but that does not mean that the study of the brain helps us to understand the mind. Provided that the brain has computational power that is equivalent to a Turing machine, this thinking goes, the physiology places no constraints on how the process of thought works. This abstraction from the brain was one of the most important merits of the cognitive revolution and has been drawn by a number of authors, notably the philosophers Fodor (1975) and Putnam (1975).[2] However, one reason for the advancing neurocognitive progress in reasoning research is the realization that universal realizability is not unqualifiedly true and thus appears to be unjustifiable as a basic assumption (Goel, 2005). A second reason for the current neurocognitive interest of reasoning researchers is that localization in the brain can help us to understand the format of mental representations. In fact, highly specific brain regions appear to be dedicated to particular representational formats. If, for example, a reasoning process is associated with brain areas that are known to respond to visual information, then this connection might support the visual reasoning theory. If a reasoning process is associated with brain areas that are typically involved in the computation of spatial information that is not necessarily visually based, then this speaks in favor of the spatial theory of reasoning. It is this commitment to testing cognitive hypotheses that distinguishes the cognitive neuroscience of reasoning from pure brain research.

This is one side of the coin. The other side, however, is that for a nonreductionist, the usual many-to-many mappings between cortical regions and cognitive functions make it almost impossible to develop cognitive theories solely on cortical grounds (see also Kosslyn, 1999; Uttal, 2001). Neural data alone are too weak to formulate cognitive theories. Only if neural data are consistent with psychological results and computational investigations can they provide reasonable support for a cognitive theory of human cognition. Based on these considerations, a further motivation for me in writing this book is to overcome both the reductionistic (looking into the brain is enough to understand the mind) and the purely mentalistic (the brain does not play a role when one wants to understand the human mind) tendencies in the cognitive sciences. Using Marr's (1982) trichotomy, in the following I seek to investigate human logical reasoning at the computational (or functional) level, the algorithmic level, and the implementational level. By applying this multilevel approach, I think it is possible to generalize about different methods and to deal with the problem that single measures—in particular, from brain-imaging techniques—are often not reliable enough by themselves to test and advance theories of how the mind works.

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