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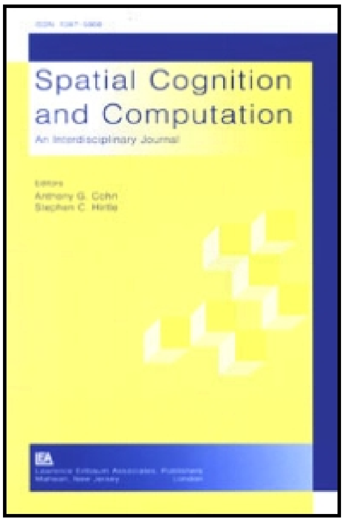


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# A Neuro-Cognitive Theory of Deductive Relational Reasoning with Mental Models and Visual Images

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**Abstract:** Many neuro-imaging studies have provided evidence that the parietal cortex plays a key role in reasoning based on mental models, which are supposed to be of abstract spatial nature. However, these studies have also shown concurrent activation in vision-related cortical areas which have often been interpreted as evidence for the role of visual mental imagery in reasoning. The aim of the paper is to resolve the inconsistencies in the previous literature on reasoning and imagery and to develop a neurally and cognitively plausible theory of human relational reasoning. The main assumption is that visual brain areas are only involved if the problem information is easy to visualize and when this information must be processed and maintained in visual working memory. A regular reasoning process, however, does not involve visual images but more abstract spatial representations—spatial mental models—held in parietal cortices. Only these spatial representations are crucial for the genuine reasoning processes.

**Keywords:** mental model, visual mental imagery, deduction, relational reasoning, visual-impedance effect

## 1. INTRODUCTION

The blue Porsche is parked to the right of the red Ferrari.
The red Ferrari is parked to the right of the green Beetle.
Is the blue Porsche parked to the left or to the right of the blue Beetle?

Individuals often say that they reason with such problems by forming a mental picture in their "mind's eye" and then look at this picture to find new information. Yet, is the subjective experience of visual imagery related to the underlying "reality" of mental representations and processes? And, why does

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reasoning seem inextricably linked with seeing in the "mind's eye"? Not only nonpsychologists, but also many cognitive psychologists have claimed that reasoning is strongly linked to imagination and thus tried to explicate how mental imagery and reasoning are interconnected (e.g., De Soto, London, & Handel, 1965; Kosslyn, 1994). There are, however, also reasons to be skeptical concerning the role of visual mental images in reasoning. For instance, if reasoning relies on visual imagination then problems that are easy to visualize should be easier to solve than nonvisual problems. The problem above, for instance, should be easier than the formally equivalent problem:

A is smarter than B.
B is smarter than C.
Is A smarter than C?

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In both problems, new information can be inferred from what is already given. Several researchers varied the imageability of such reasoning problems but did not find any differences between problems that are easy or difficult to visualize (e.g., Johnson-Laird, Byrne, & Tabossi, 1989). Neuro-imaging studies sometimes find neural activity in vision-related brain areas during reasoning with such problems, and sometimes no such activity is found. Moreover, computational systems of human reasoning show that human reasoning performance can be properly reconstructed without visual images (Ragni, Knauff, & Nebel, 2005; Schlieder, 1999; Schlieder & Berendt, 1998). So what really happens in our brains if we subjectively experience visual mental images during reasoning? The aim of this paper is to resolve the inconsistencies in the previous literature on reasoning and imagery and to make first steps towards a neurally and cognitively plausible theory of human reasoning. Currently, this theory is only concerned with a special form of reasoning, *deductive relational reasoning* (as in the examples above) and does not imply that the suggested mechanisms also work the same way in other forms of reasoning, such as conditional or syllogistic reasoning. However, as relational inferences are by far the most important forms of reasoning in the domain of *spatial cognition and computation*, the present approach should be interesting for cognitive psychologist as well as for computer scientists, geographers, and other spatial cognition researchers. Readers who are interested in the neural basis of other forms of reasoning (including syllogisms and conditional inferences) can find two up-to-date reviews in Knauff (2007) and Goel (2007). In Knauff (2007) the interested reader can also find some findings on impaired reasoning abilities after brain injuries.

The main theoretical assumption of the present paper is that the same sort of *spatially organized mental models* underlie all forms of relational reasoning and that these models are not to be identified with visual images. We might "see" a visual image for the inference with the cars (example 1 above) but not for the second with the "smart"-relation. However, what matters is not our subjective experience, but rather what is processed by our cognitive system. The paper starts with a brief overview of previous findings on reasoning and mental imagery. Then it reports a number of neuro-imaging studies (partly coming from our own lab) that explored the involvement of visual brain areas in reasoning. Then a recent event-related fMRI study is reported, that for the first time disentangles the neuro-cognitive subprocesses underlying different stages in the reasoning process, and at the same time overcomes the potential visual confound in the previous studies on the neuronal basis of human reasoning.

Based on these findings and several behavioral results a *neuro-cognitive three-stage-theory of reasoning with mental models and visual images* is proposed. While many studies have implied that visual images play a key role in the reasoning process, in this account visual brain areas are only involved if the problem information is easy to visualize and when this information must be processed and maintained in visual working memory. A regular reasoning process, however, does not involve visual images but more abstract spatial representations—spatial mental models—held in parietal cortices. Only these spatial representations are crucial for the genuine reasoning processes. If, however, the spatial information must be retrieved from a visual image in order to construct the appropriate spatial mental model (as in the problem with the red, blue, and green cars) additional processes come into play and can even impede the process of reasoning.

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## 2. SOME HISTORICAL ROOTS AND BEHAVIORAL FINDINGS

During the early decades of the last century, a fierce academic debate about the role of images in human cognition took place in research psychology. Although the functions of the sensory systems were still of great interest to psychologists, another particular area of attention was now the role of visual imagery in thinking, reasoning, and problem solving. On the one hand, in 1910 Cheves Perky discovered that mental imagery supports visual perception and that people often merge mental images and what is actually seen. In other words, visual imaginations can be so similar to real perceptions that they can be mistaken for the latter (Perky, 1910). On the other hand, in particular the "Würzburger Schule" promoted the assumption that thinking is possible without imagination. The claim was supported in an experiment by Karl Bühler, who asked participants, for instance, "Does a man have the right to marry the sister of his widow?" and afterwards asked them what had happened in their mind. Not one of the participants reported experiencing visual images. From his findings, Bühler concluded that thinking is possible without seeing in the mind's eye (Bühler, 1909). However, other authors criticized the idiosyncrasy of Bühler's problems and for a long period of time, for most researchers it was a matter of fact 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, mainly in Anglo-American psychology, publications on mental imagery engendered much controversy. Cognitive psychologists avoided the concept of imagery, given the harsh criticism it had received from behaviorists (Watson, 1913). In contemporary psychology, however, a wide range of evidence is compatible with the assumption that imagery is a vital part of human cognition, including the well-known studies of mental rotation, the mental scanning of images (cf. Kosslyn, 1980; Shepard & Cooper, 1982), and studies on the relationship between imagery and creative problem-solving, suggesting that visualization facilitates innovative solutions (Suler & Riziello, 1987; Antonietti, 1991; recent results in: Denis, Logie, Cornoldi, de Vega, & Engelkamp, 2001). Moreover, subsequent to the well-known imagery debate in the 1980's (overview in: Block, 1981; Tye, 1991), the majority of cognitive researchers agree on the assumption that cognitive processes can rely on a number of different representational formats.

Starting in the 1960s, cognitive psychologists also began to explore the role of visual images in *relational* reasoning. The two problems above are examples of such inferences. In the psychology of reasoning, such problems are called *transitive inferences, linear syllogisms,* or *three-term-series problems* (Johnson-Laird, 1972; Sternberg, 1980). The problem information is given by the two statements which are called *premises*, and the task is to find a *conclusion* that necessarily (logically) follows from these premises. Adding further premises, changing the order of premises and terms, etc., can result in more complex problems (overviews can be found in Evans, Newstead, & Byrne, 1993 or Manktelow, 1999).

A pioneering reasoning study was carried out by De Soto, London, and Handel (1965), who argued that reasoners represent the entities of a relational reasoning problem as a mental image and then "read off" the conclusion by inspecting the image. Huttenlocher (1968) also argued that reasoners imagine an analogous physical arrangement of objects in order to cope with reasoning problems. Moreover, other authors report 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). However, several studies have failed to detect any effect of imageability on reasoning. Johnson-Laird, Byrne, and Tabossi (1989), for instance, examined reasoning with relations that differed in imageability—for example, equal in height, in the same place as, and related to (in the sense of kinship)—and did not find any effect on reasoning accuracy. Newstead, Pollard, and Griggs (1986) reported a similar result. There were also some studies that explored the individual differences between "good" and "poor" "imagers". A classical paper is that by Paivio (1970) who reported quite low correlations between self-reported imagery vividness with individual differences in functional performance in thinking and problem solving. Sternberg (1980) did not find any

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reliable correlation between scores on the imageability items of IQ-tests and reasoning ability. Overall, for a long time the results from many behavioral studies have been inconclusive and have left many questions unresolved.

## 3. FINDINGS FROM BRAIN IMAGING

With the development of new brain imaging methods the debate shifted from the behavioral findings towards the question of how reasoning and mental imagery is biologically realized in the human brain. Broadly speaking, the occipital lobe processes visual information. However, it is not only responsible for visual perception, but also contains association areas and appears to help in the visual recognition of objects and shapes. The occipital cortex can be divided into the primary visual cortex, also referred to as striate cortex or, functionally as V1, and to the visual association areas, also called the extrastriate cortex, or V2, V3, V4. The primary visual cortex receives visual input from the retina and is topographically organized, meaning that neighboring neurons have receptive fields in neighboring parts of the visual field. According to the cytoarchitectonic map of Brodmann (1909) this region is called Brodmann's area (BA) 17. The visual cortices have been frequently related to visual mental imagery. For instance, patients who are blind in one side of the visual field are also unaware of objects on that side when imagining a visual scene. If the patients turn the mental image around so that they had to "look" at the image from the opposite direction, they reported objects on the other side and ignored those which they had previously reported "seeing" (Bisiach & Luzzatti, 1978; Della Sala, Logie, Beschin, & Denis, 2004; Logie, Della Sala, Beschin, & Denis, 2005).

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The strictest form of imagery theories has been elaborated on in the influential book by Kosslyn (1994). In this book, Kosslyn claims that during mental imagery the geometrical information of remembered objects and scenes are processed in the primary visual cortex. Consequently, one of the central research issues on imagery is whether the primary visual cortex and nearby cortical areas are activated by visual mental imagery. Indeed, this assumption is supported by a series of studies by Kosslyn and his colleagues, who found increased blood flow in BA 17 during mental imagery of letters (Kosslyn, Alpert, Thompson, et al., 1993) and objects of different sizes (Kosslyn, Thompson, & Alpert, 1997). Moreover, if participants imagined a letter, the larger letters activated a larger region of V1 while the smaller letters activated a smaller region (Kosslyn et al., 1993). Additional support for the strong imagery theory comes from studies by Kosslyn et al. (1999), Sabbah et al. (1995), and Chen et al. (1998).

More moderate approaches to visual mental imagery are related to the complete ventral pathway. Beyond the striate cortex, the ventral pathway (e.g., Farah, 1984), or "what" system, comprises parts of the temporal lobes (Ungerleider & Mishkin, 1982). The most important areas are the inferior temporal (IT) cortex that typically responds to properties of objects, such as shape, texture and color. The anterior parts of the system processes information in a visual code and cannot be assessed by other modalities—hence, the system is modality-specific. The main function of the system is to identify objects, i.e., compare stored objects with the object that is viewed. However, this pathway can also run in the opposite direction so that visual images can be generated top-down from memories.

Outside the occipital areas, the dorsal pathway, or "where" system, comprises parts of the two parietal lobes. They contain the primary sensory cortex which controls sensation and large association areas. The posterior parietal cortex (PPC) and the precuneus are considered as areas that combine information from different sensory modalities to form a cognitive representation of space. Although these areas have diverse functions and use a variety of sensory modalities, they are all responsible for processing information about spatial relationships (Andersen, 1997).

The frontal cortex is involved in planning, problem solving, selective attention, and many other higher cognitive functions (including social cognition and emotion). The anterior (front) portion of the frontal lobe is called the prefrontal cortex. It is involved in executive processes in working memory and typically implicated when several pieces of information in working memory need to be monitored and manipulated. A related function is that the region underlies the integration of multiple relations. Waltz et al. (1999), for instance, showed that patients with damage to the prefrontal cortex were strongly impaired in any sort of reasoning calling for the integration of relations, whereas they performed normally in episodic and semantic memory tasks.

Early brain imaging studies on reasoning found little evidence that visual brain areas (in occipital cortex) are involved in reasoning (Goel, Gold, Kapur, & Houle, 1997, 1998). Then, however, an increasing number of studies reported activity in primary and secondary visual areas when participants were engaged in reasoning problems. This, for instance, was the case in a study by Goel, Buchel, Frith, & Dolan (2000) in which the volunteers had to solve different kinds of relational inferences. Moreover, Knauff, Kassubek, Mulack, Salih, and Greenlee (2002) studied relational and conditional inferences that were presented acoustically via headphones to the participants (to avoid a confounding of mental imagery and visual perception). In this study, both types of reasoning problems resulted in activity in a bilateral occipitoparietal-frontal network distributed over parts of the prefrontal cortex, the inferior and superior parietal cortex, the precuneus, and the visual association cortex. Similar results have been reported in Ruff, Knauff, Fangmeier, and Spreer (2003). Here we scanned the brain activity of our participants and also measured their visuospatial ability with a well-known subset of tasks from an intelligence inventory. Interestingly, the brain activation was significantly modulated by the participants' visuospatial skill. The higher the participants' visuospatial skill, the better their reasoning performance, and the less activation was present in visual association areas during reasoning. This pattern agrees with

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recent findings on the effects of skill level on neuronal activity. Accordingly, the reasoning problems seemed to have placed less demand on the visuo-spatial processing resources of participants with high skill levels, so that less activity in the relevant cortical regions was required.

## 4. DISENTANGLING VISUAL AND SPATIAL PROCESSES IN REASONING

Studies from the literature and our earlier findings provide informal evidence that reasoning is occasionally accompanied by visual mental imagery. Alas, these studies were not designed to determine the exact role of visual images in reasoning and thus examined the brain activation during the whole reasoning process in a blocked fashion (e.g., Knauff, Mulack, Kasubek, Salih, & Greenlee, 2002) or just compared the neuronal processes during the conclusion of the reasoning problem with the presentation of irrelevant control sentences (e.g., Goel & Dolan, 2001). In both paradigms it is impossible to determine whether the activity in occipital brain areas pointing to the employment of visual mental imagery is associated with the processing of premises, their maintenance in working memory, or with the actual reasoning process. Reasoning-related processes during different stages of problem processing and other cognitive processes are inseparably mixed. To overcome these disadvantages, recently an fMRI study has been conducted to disentangle the neuro-cognitive subprocesses underlying the different stages in the reasoning process and at the same time to avoid potential confounds in the previous studies on the neuronal basis of imagery and reasoning.

In the study, the brains of our participants were scanned while they solved relational reasoning problems (Fangmeier, Knauff, Ruff, & Sloutsky, 2005; Knauff, Fangmeier, Ruff, & Sloutsky, 2005). Since the aim was to keep apart the pure reasoning process from the maintenance of information in working memory, in a second group of tasks participants had to simply keep the premises of the identical problems in working memory without making inferences. To avoid the need to read the premises and conclusions the sentences were replaced by graphical arrangements describing the spatial relations between three objects. The reasoning problems contained two premises and a conclusion and the participants had to decide whether the conclusion logically (necessarily) followed from the premises. Here is an example of a reasoning task with a valid conclusion:

| | | |
|---|---|---|
| Premise 1: | V | X |
| Premise 2: | X | Z |
| Conclusion: | V | Z |

A sentential version of the given example would be: “V is to the left of X” (first premise) and “X is to the left of Z” (second premise). From these

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premises it follows “V is to the left of Z” (conclusion). In the maintenance problems, the presentation of the two premises was the same as in the reasoning task, but the participants had to decide whether the term order of the third sentence was identical to one of the previous premises or not. Thus, no inference between the two premises had to be made. Moreover, the processing of the first premise, the second premise and the conclusion was time-locked to the presentation of the arrangements. Thus, the brain activity elicited by different stages of the reasoning process could be examined.

The results of this study are illustrated in Figure 1. The darker a region in the image indicates that more cortical activity was measured. As can be seen from the foci of activation, three distinct patterns of neuronal activation associated with three stages of the reasoning process could be identified. During the presentation of the first premise, reasoners had to process and maintain the spatial relation between the first two objects in working memory. During this stage two large bilateral clusters of activation were found in the vision-related occipito-temporal cortex (see Figure 1a). Then the participants needed to unify the second premise with the information from the first premise in order to construct an integrated representation of both premises. During this stage the two clusters in the occipito-temporal cortex and an additional cluster in the anterior prefrontal cortex (AFC) were activated. The latter cluster covered parts of the middle frontal (BA 10) and medial frontal gyrus (BA 32; see Fangmeier et al., 2005, for details). In the third stage participants had to inspect and manipulate this representation to draw a putative conclusion and to compare this conclusion with the displayed conclusion. They indicated by pressing a button whether the displayed conclusion is “True” or “False.” Crucially, this stage activated clusters in the dorsolateral prefrontal cortex (DLPFC) and in the spatial areas of posterior parietal cortex, whereas vision-related activity in occipital cortex completely disappeared.

The contrasts between the reasoning and maintenance of premises were carried out to separate the pure reasoning process from the maintenance of information in working memory. It is critical to appreciate that the processing of the matched maintenance problems also proceeded in three stages, but that participants only had to remember the premises and match them with

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***Figure 1.*** (See artwork on page 117.) Images representing differentially activated brain areas during the three stages of reasoning and maintenance. The brain is presented from three different perspectives: from the side (as if vertically cut through at about the position of the eyes), transverse (as if vertically cut through in parallel to the axis between the ears), and horizontal (as if horizontally cut through in parallel to the axis of the eyebrows). The clusters on the upper group of displays indicate the activity for the reasoning tasks during (a) premise processing stage, (b) integration stage, (c) validation stage. The clusters on the lower group of displays show the activity in the maintenance tasks during (d) premise processing stage, (e) premise maintenance stage, (f) validation stage (from Fangmeier et al., 2005; see text for details).

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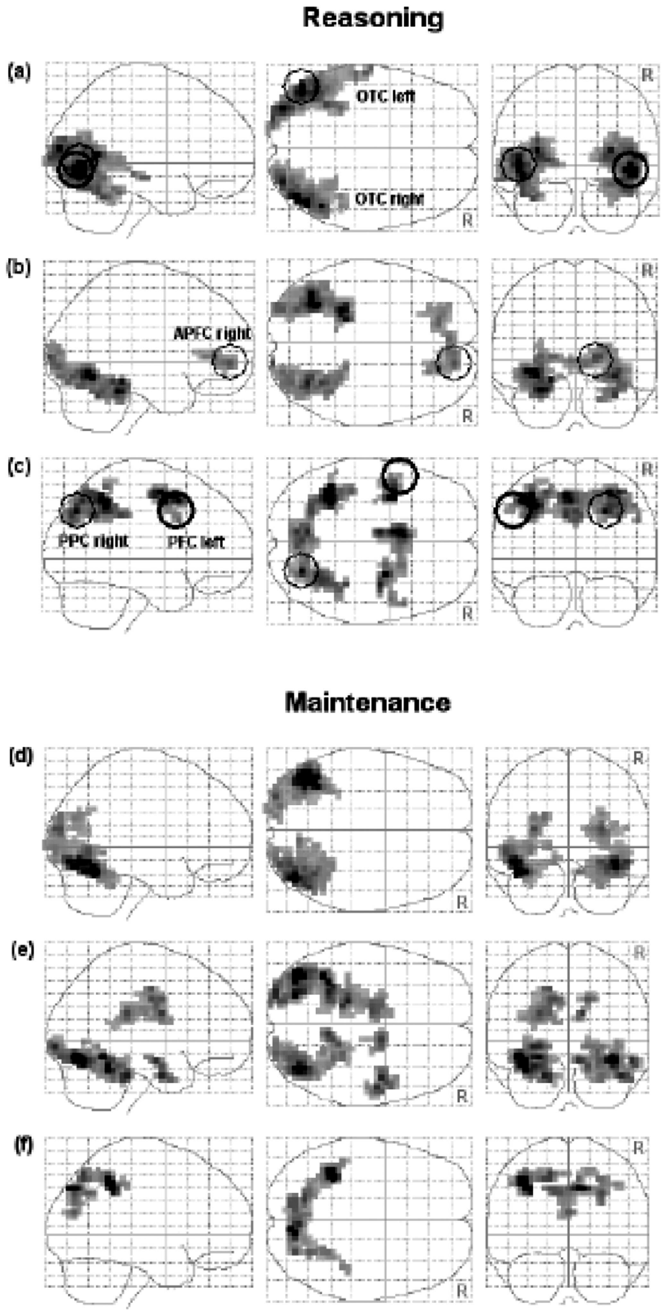


*Figure 1.* See caption on page 116.

the presented third arrangement. They did not make any inferences. As also shown in Figure 1, the patterns of activity were similar only in the first stage but significantly differed from reasoning in the second and third stages. During the first stage of the maintenance problems, again activity in the two large bilateral clusters in the vision-related occipito-temporal cortex were found such that we also obtained during reasoning (compare Figure 1a with 1d). In the second stage, which now required only premise maintenance but not integration, similar activation in occipital areas was found, but crucially no frontal activation (compare Figure 1b with 1e). Finally, during the third stage of the maintenance problems, there were significantly lower prefrontal activations, and less extensive activation in space-related parietal areas than during the reasoning problems (compare Figure 1c with 1f).

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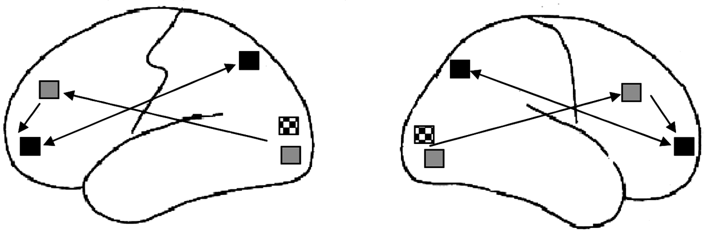
## 5. A NEURO-COGNITIVE THEORY OF DEDUCTIVE RELATIONAL REASONING WITH MENTAL MODELS AND VISUAL IMAGES

As there is a many-to-many mapping between cortical regions and cognitive functions, neuropsychological data alone are too weak to formulate cognitive theories. However, if imaging data are consistent with behavioral findings this can provide strong support for a cognitive theory of human reasoning. The following section uses this connection between behavioral findings and neuropsychological results to introduce a neuro-cognitive theory of human (relational) reasoning that accounts for the different functions of visual *and* spatial representations in reasoning.

Take, for instance, the example at the beginning of this article. Reasoners might imagine three cars—(the red and blue sport wagons and the green Volkswagen)—in a vivid visual image and think that they should use this image to find a relation not explicitly given in the premises. However, let us use a more neutral version of the problem to explain what could really happen during reasoning. Psychologists often use problems with tools, fruits, vegetables, etc., because they are easier for their participants to visualize and have less to do with their prior knowledge (Knauff & Vosgerau, 2009). So imagine, for instance, the formally equivalent inference problem:

The hammer is to the right of the pliers.
The pliers are to the right of the screwdriver.
Does it follow that the hammer is to the right of the screwdriver?

The findings by Fangmeier et al. (2005) indicate that such inferences depend on three neuro-cognitive stages of thought. In the following I refer to these stages as (1) *visual image construction*, (2) *image-to-model transformation*, and (3) *mental model processing* (see Figure 2) and will show that this distinction is consistent with many behavioral findings.



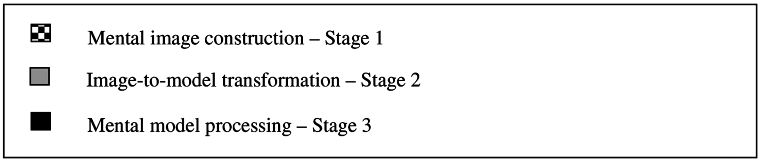



***Figure 2.*** Schematic illustration of the Neuro-Cognitive Theory of reasoning with mental models and visual images.

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*Visual Image Construction.* The reported data show that this stage relies on neural processes in the occipito-temporal cortex that are known to be involved in visual mental imagery and visual working memory. The most reasonable account for this finding is that the processing of the first premise spontaneously elicits visual imagery. Reasoners seem to use their background knowledge to construct a *visual mental image* of the information from the premise. They, for instance, imagine the tools lying on a table or on the floor of their garage. Two sorts of knowledge are needed for this visual image construction: knowledge about the visual features of the objects and knowledge referring to the meaning of the spatial expressions. The former is provided by the visual pathway that is known to run in two directions. Processing during perception begins with a retinotopic representation in the occipital cortex, and progresses to memory representations of objects in areas of the temporal cortex. However, visual images also can be generated top-down from memories: visual information stored in memory travels backwards from the temporal regions of the ventral pathway into the occipital cortex where it evokes a pattern of activity that is experienced as a mental image (Farah, Hammond, Levine, & Calvanio, 1988). For knowledge about spatial relations a similar mechanism exists. One of the best investigated areas of the brain is the posterior (back) part of the parietal cortex which receives projections from extrastriate visual areas and projects to areas associated with saccadic eye movements. In the present context, however, it is important that these areas of the dorsal pathway form a mental representation of space. During perception spatial relations are extracted from the retinotopic representations in the occipital cortex, and result in memory representations in the posterior parietal cortex (PPC).

However, this spatial information can also be generated top-down from memory so that an object from the ventral pathway (e.g., the tools in the example) can be located in the visual image. The resulting visual image is structurally similar to a real visual perception and relies on similar brain functions. Like a visual percept, it might represent colors, shapes, and metrical distances. It probably can be rotated and scanned and it might have a limited resolution (cf. Johnson-Laird, 1998; Kosslyn, 1994). It is reasonable to assume that these representations of the premises are responsible for the experience of visual images during reasoning. Reasoners might be aware of the visual images, but they probably do not have conscious access to what is going on in the next steps of the inference.

*Image-to-Model Transformation.* The essential finding for this stage is the activity in the anterior prefrontal cortex (AFC). Neural computations in these areas seem to bridge the gap between the visual image of the premises and the third stage of reasoning, where vision-related activity in the occipital cortex completely disappears and is replaced by large activated clusters in spatial brain areas in the posterior parietal cortex (PPC). The most plausible explanation for this finding is that the actual reasoning is based on spatial representations and the visual images of the premises are not pertinent to the reasoning processes. Therefore, the spatial information must be *retrieved* from the visual image in order to construct the appropriate spatial mental model for making the inference.

Thus, there must be a mechanism that transforms visual representations into spatial ones. The resulting spatial representations might be, as many results suggest, *mental models* in the sense of Johnson-Laird (1983) and Johnson-Laird and Byrne (1991). Such models represent the information pertinent to reasoning by means of spatial relations. In inferential tasks, the resulting spatial representations are likely to exclude visual detail, to represent only the information relevant to the inference. They take the form of a representation that maintains the spatial relations between objects in a multidimensional array. According to model theory, such a spatial representation of the premises above could be the following:

screwdriver pliers hammer

There is substantial evidence to suggest that the anterior prefrontal cortex is involved in the processing of relations. Specifically, this area has been found to be involved in relational integration during reasoning or in considering multiple relations simultaneously (e.g., Waltz, Knowlton, Holyoak, Boone, Mishkin, et al., 1999; Christoff, Prabhakaran, Dorfman, Zhao, Kroger, et al., 2001). Relational integration appears to be a specific kind of mental computation that develops slowly in humans—much as deductive reasoning ability does (cf. Evans, Newstead, & Byrne, 1993). Moreover, the neural computation is strongly influenced by the number of relations that must be

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considered. Halford, Wilson and Phillips (1998) distinguished three levels of complexity: in 0-relational problems no relations need to be considered; in 1-relational problems, a single relation must be considered, and 2-relational problems in which two relations must be considered simultaneously and, thus, integrated. All problems from the fMRI studies reported here belong to the last group of problems because exactly two relations must be retrieved from the visual images. In the example here, it is the relation between the hammer and the pliers and the relation between the screwdriver and the pliers. It is important to see that the third relation, namely that between the hammer and the screwdriver, does not need to be explicitly represented because it can be read off from the model. Moreover, it is essential to see that these processes are unlikely to be accessible to the conscious experience of the individual. The reasoner still just experiences the image of the premises.

*Mental Model Processing.* In the final stage, activation was found in the bilateral PPC and the dorsolateral prefrontal cortex (DLPFC). While the other two stages were basically concerned with the visual image and its transformation into a spatial model, this stage lies at the heart of reasoning. Now the spatial mental model must be processed by logical routines. The maintenance and handling of spatial representations is known to be managed by regions in the PPC. According to many studies, the PPC plays a crucial role in the processing of spatial information from different modalities (Burgess, Maguire, Spiers, & O'Keefe, 2001) and in the integration of sensory information from all senses into egocentric spatial representations (Andersen, Snyder, Bradley, & Xing, 1997; Bushara, Weeks, Ishii, Catalan, Tian, et al., 1999; Colby & Duhamel, 1996; Xing & Andersen, 2000). Crucially, these areas are not exclusively dedicated to information coming from visual perception.

Several studies show that areas in the PPC bring spatial information from all perceptual systems into the same reference system. Another important finding is that of the laterality of the human PPC. Kosslyn et al. (1989) have shown that there are two different subsystems processing quantitative-metrical and qualitative-categorical spatial information (see also: Kosslyn, Chabris, Marsolek, & Koenig, 1992). Metrical spatial information is that in which exact distances with respect to a continuous coordinate system are represented, and Kosslyn located this system in the right hemisphere. In contrast, categorical spatial information is that in which spatial relations between objects are represented qualitatively by discrete spatial concepts. Although these relations are presumably not represented in a language-based format, the concepts may correspond to verbal expressions such as left and right, above and below (Knauff, 1999).

According to model theory, the spatial representation captures one situation that is possible, given that the premises are true (Johnson-Laird, 1983; Johnson-Laird & Byrne, 1991). Like a spatial diagram, the model's parts correspond to the parts of what it represents, and its structure corresponds to

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the structure of the reasoning problem (Johnson-Laird, 2001). In other words, a mental model is a representation of objects and relations that constitutes a model (in the usual logical sense) of the premises given in the reasoning task. According to the model theory, reasoning with this model relies on processes that inspect and validate the model. The inspection yields new information that is not explicitly given in the premises and the validation checks whether a putative conclusion is actually true. As computational models suggest, the inspection process can be functionally described as a shift of a spatial focus that checks the cells of a spatial array and "knows" from the scan direction the relation between two objects in the array (Ragni, Knauff, & Nebel, 2005; Schlieder & Berendt, 1998).

In the present account, the model is represented in the neural tissue of the partial cortex and the inspection and validation processes are controlled by computations in the PFC. It is very likely that reasoners are not aware of all of these processes, because deductive reasoning—like fundamental memory processes—has to be performed extremely fast and accurately, and must be sheltered from external disruptions. Nevertheless, the current account is suggested by many studies on cognitive control, characterizing sections of the PFC as typically involved when several pieces of information in working memory need to be monitored and manipulated (Petrides, 2000). Moreover, patients with damage to the prefrontal cortex are strongly impaired on deductive (and inductive) reasoning tasks whenever these require the processing of relations (e.g., Waltz et al., 1999). Together with our present findings, this indicates that structures in the PFC and PPC strongly interact during reasoning. Parietal areas are concerned with the mental model itself and the PFC is responsible for controlling the inspection and manipulation of this model. Normally, these processes work error-free and thus results in a valid conclusion, i.e., that in the example above the screwdriver is to the left of the hammer. Errors do occur, however, because reasoning performance is limited by the capacities of the systems, the misunderstanding of the premises, or the ambiguity of problems (Evans et al., 1993; Johnson-Laird & Byrne, 1991; Manktelow, 1999). See Figure 2.

Although the account is not yet spelled out in all details, it resolves many inconsistencies in previous neuro-imaging studies on reasoning. These studies have similarly implied that the parietal cortex may play a key role in reasoning based on mental models, which are supposed to be of abstract spatial nature. However, these studies have also shown concurrent activation of visual association cortices (Goel & Dolan, 2001; Goel, Büchel, Frith, & Dolan, 2000), which have often been interpreted as evidence for the role of visual mental imagery in reasoning (Ruff, Knauff, Fangmeier, & Spreer, 2003). The present account makes this role of images clearer. It shows for the first time that visual brain areas might be involved in premise processing and the construction of an initial visual image of the situation described in the premises. These processes, however, are not specific to reasoning,

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but primarily related to the comprehension of premises and their visual representation in working memory.

The actual reasoning process then relies on more abstract spatial representations held in parietal cortices. Because initially a visual image had been constructed from the premises, the spatial information relevant for reasoning must be retrieved from this image in order to construct the appropriate spatial mental model for making the inference. The inspection and manipulation of these spatial mental models is crucial for subsequent processes and the supplementary activation in the DLPFC and AFC during reasoning indicates that further processes are exclusively devoted to the processing of relations and executive control processes. Individuals might be aware only of the visual images, but it is possible that we do not have conscious access to the spatial representations and the processes that inspect and manipulate these representations, although they underlie our reasoning abilities.

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## 6. ADDITIONAL EVIDENCE FOR THE THEORY

The theory presented here relies on two major conjectures: visual images are involved in the processing and maintenance of premises in working memory, but not in the actual reasoning process. And: the spatial relations from the premises must be integrated into one spatial mental representation—the mental model—in order to make the inference. This spatial model then can be further processed by logical routines that inspect and manipulate the model. Both assumptions are supported by further experimental findings.

*Conjecture 1: Visual Images Are Involved in the Processing and Maintenance of Premises in Working Memory.* Support for this claim comes from two groups of studies. First, countless studies in the field of text comprehension have shown that visual representations are routinely and immediately activated during word and sentence comprehension. If individuals are asked to read texts but were given no instruction to form visual images they regularly experience visual images while reading (cf. Sadoski & Paivio, 1994). Most of the explanation is more or less inspired by the well-known dual-coding theory in which cognition relies on two separate but interconnected systems: a verbal system for language and a nonverbal system that deals with visual images (Paivio, 1971, 1986). Today, almost everybody in reading research has no doubt that mental imagery occurs as a spontaneous process in reading and that images have powerful effects on comprehension, recall, recognition, and the reception of the text (e.g. Glenberg, 1997; Sadoski, 1985, Sadoski & Paivio, 1994, Stanfield & Zwaan, 2001; Zwaan, Stanfield, & Yaxley, 2002).

Evidence that visual images are primarily involved in the processing and maintenance of premises in working memory also comes from the comparison of reasoning and maintenance problems. An initial study has been conducted by Ruff et al. (2003), who examined the differences between both tasks in a blocked design. Interestingly, neuronal activations common to reasoning and maintenance were detected bilaterally in secondary visual cortices. This again indicates that the occipital activation patterns were not related to reasoning, but rather to the mere encoding and maintaining of premises in visual working memory. A second finding was that only reasoning led to more activation than maintenance bilaterally in the dorsolateral prefrontal cortex and in the anterior prefrontal cortex.

As already mentioned Waltz et al. (1999) showed that patients with damage to the prefrontal cortex were strongly impaired on deductive and inductive reasoning tasks whenever these required relational integration. Waltz et al. concluded that "postulating a neural system for integrating multiple relations provides an explanation of why a wide range of tasks, all of which depend on processing multiple relations simultaneously, are sensitive to prefrontal damage and activate DLPFC" (p. 124). For the present account it is essential that relational integration is a vital part of reasoning with transitive inferences, while it is not required for solving the maintenance problems.

*Conjecture 2: Premises during Reasoning Are Integrated into One Unified Mental Representation and This Representation Is Inspected to Find New Information.* This assumption is also supported by two groups of findings. The first is related to the work on relational integration and the connection between complexity and number of relations (Halford et al., 1998). Christoff et al. (2001) tested the hypothesis that the process of relational integration is a component process of complex reasoning and that it recruits PFC. They examined brain activation during 0-relational, 1-relational, and 2-relational problems and found that PFC is more activated by 2- than by 1-relational problems and by 1-relational problems more than by 0-relational problems. This link between neural activity and the number of relations reflects that relations must be integrated into one unified representation and this is associated with processes of manipulating self-generated new information.

The second group of supporting studies is linked to mental models research. An important prediction of model theory is that the ease of reasoning is a function of the difficulty to integrate the information from the premises into a unified representation. Hence, Ehrlich and Johnson-Laird (1982) gave subjects the premises of a transitive inference in continuous (A $r_1$ B, B $r_2$ C, C $r_3$ D), semi-continuous (B $r_2$ C, C $r_3$ D, A $r_1$ B), and discontinuous (C $r_3$ D, A $r_1$ B, B $r_2$ C) premise orders (the letter r stands for a certain relation). Subjects had to infer the conclusion A $r_4$ D and the results showed that continuous order (37% error) is easier than discontinuous order (60% error), and there is no significant difference between continuous and semi-continuous (39% error) tasks. This finding is an effect of the difficulty of integrating the information from the premises into a unified representation because in the continuous and semi-continuous orders, it is possible to integrate the information of the first two premises into one representation—a mental model—at the outset,

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whereas when they are presented with the discontinuous order, subjects must wait for the third premise in order to integrate the information in the premises into a unified representation.

Similar results are reported, for instance, in Carreiras and Santamarìa (1997) and in Knauff, Rauh, Schlieder, and Strube (1998a). In Knauff et al. (1998a) there was no significant difference in the percent of errors between continuous (39.7%) and semicontinuous (40.1%) premise orders, but both were significantly easier than the discontinuous order, which lead to 50.0% errors on average. Moreover, the data on premise processing times showed that the discontinuous premise order reliably increases the processing time for the third premise, because information from all premises must be integrated at this point (see Table 1, Exp. 1 from Knauff, Rauh, Schlieder, & Strube, 1998a). Similar findings are reported from experiments in which the order of the terms within the premises was varied rather than the order of the premises. In parallel to the effect of premise order, these studies also indicate that the difficulty of reasoning tasks depends on the cognitive effort needed to integrate the premise information into a unified mental representation (Exp. 2 from Knauff et al., 1998a).

The strongest argument in support of premise integration is the difference between determinate tasks, in which only a single model can be constructed (as in our fMRI studies) and indeterminate tasks that call for multiple models. Byrne and Johnson-Laird (1989) compared such problems and found that indeterminate problems (34% correct) are reliably harder than determinate problems (61% correct). According to the mental model theory, indeterminate problems are more difficult because the construction of more than one integrated representation is more difficult than constructing a single model.

In our group, we have extensively investigated reasoning with indeterminate problems, and may have found the most convincing evidence for premise integration. The mental model theory ought to explain the integration process as a serial process that always produces the same first mental model. Hence, we tested the assumption of the existence of generally *preferred mental models* in an experiment in which subjects had to determine possible relationships between objects based on the information given in the premises.

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**Table 1.** Premise processing times for the first, second, and third premises in the tasks with continuous, semi-continuous, and discontinuous premise order

| Premise order | Premise 1 | Premise 2 | Premise 3 |
|---|---|---|---|
| Continuous | 13.0 | 11.2 | 10.9 |
| Semicontinuous | 13.6 | 11.0 | 14.4 |
| Discontinuous | 12.4 | 13.9 | 19.5 |

Note. From Knauff et al. (1998a).

The indeterminate problems called for three, five, or nine possible models. The results showed that whenever a reasoning problem has multiple solutions, reasoners prefer one of them and that individuals consistently prefer the same solution. This suggests that participants indeed integrate the information from the premises and inspect unified mental representations to find new information not given in the premises (Knauff, Rauh, & Schlieder, 1995; Rauh, Hagen, Knauff, Kuß, Schlieder, & Strube, 2005; Vandierendonck, Dierckx, & De Vooght, 2004).

## 7. HOW TO EXPLAIN THE VISUAL-IMPEDANCE EFFECT?

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So far, we were only concerned with reasoning problems that invoke visual images. But what happens if the premises of a reasoning problem do not bias the reasoner to construct visual images? For example, they could straightforwardly lead to the spatial representations pertinent to reasoning without the phenomenal experience of an image. Are visual images *necessary* for reasoning? Do they have a *causal power* in the reasoning processes? Or are they only an *epiphenomenon*, a side-effect of reasoning? The most convincing support for the three-stage theory is provided by a combined behavioral and neuro-imaging study that was specifically designed to answer these questions. In this study, we systematically investigated the engagement of mental imagery and the related brain areas during reasoning (Knauff, Fangmeier, Ruff, & Johnson-Laird, 2003). We speculated that only premises that are easy to visualize spontaneously elicit visual images, while other premises do not push reasoners to construct visual images. For instance, it is likely that reasoners construct a visual image from premises such as "The blue Porsche parks to the right of the red Ferrari" or even from "The screwdriver is to the left of the hammer." But what about premises such as those in the second example from the introduction ("A is smarter than B", "B is smarter than C")? These premises are much more difficult to visualize and, therefore, probably no visual images are pressed into service during reasoning. Is reasoning easier or more difficult with these relations and does it activate different brain areas? In Knauff and Johnson-Laird (2002) we empirically identified four sorts of relations: (1) visuospatial relations that are easy to envisage visually and spatially, (2) visual relations that are easy to envisage visually but hard to envisage spatially, (3) spatial relations that are hard to envisage visually but easy to envisage spatially, and (4) control relations that are hard to envisage either visually or spatially. Then, we started by conducting a series of behavioral experiments in which participants solved transitive inferences with these relations (Knauff & Johnson-Laird, 2002). Apparently, the orthodox imagery theory would predict an advantage of visual and probably visuospatial relations. Our prediction, however, was that relations that elicit visual images containing details that are irrelevant to an inference should impede the process of reasoning, because the information pertinent to reasoning must be retrieved from the image. In contrast, relations that directly yield a spatial model without the "detour" of a visual image should speed up the process of reasoning in comparison with relations that elicit images.

Our findings supported these predictions: in three experiments we found relations that are easy to visualize impaired reasoning. Reasoners were significantly slower with these relations than with the other sorts of relations. In fact, the spatial relations were the quickest, while the visual relations were the slowest. We called this the *visual-impedance effect* (Knauff & Johnson-Laird, 2002).

We then performed a brain imaging study using the same sorts of problems. As can be seen in Figure 3, all types of reasoning problems again evoked activity in the parietal cortices. This activity seems to be a "default mode" of brain functioning during reasoning, because individuals might have the facility to construct mental models from all sorts of relations. Such models will be spatial in form for visuospatial and spatial relations, and, as longstanding evidence suggests, even relations such as "smarter" are also likely to elicit spatial models (see, e.g., Johnson-Laird, 1998; De Soto et al., 1965). However, only the problems based on visual relations also activated areas of the visual cortices. Presumably, in the case of visual relations such as "The blue Porsche is parked to the right of the red Ferrari." reasoners cannot suppress a spontaneous visual image of the appearance of the cars parking in front of a night club. Its construction calls for additional activity in visual cortices and retards the construction of a spatial mental model that is essential for the inferential process.

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A study by Knauff and May (2006) provides remarkable extra evidence for this account. One consequence from the present account is that people who are unable to construct visual images should be not disrupted by the visual details in the premises. This hypothesis has been tested with a group of congenitally totally blind participants. On the one hand, a visual account of reasoning might suggest that congenitally totally blind individuals—that do not experience visual mental images—should be impaired in reasoning with highly visual premises (e.g., Fraiberg, 1980). On the other hand, there are several studies showing that persons who are blind from birth differ from sighted people in their use of *visual* images, but that they are as good as sighted in the construction of *spatial* representations (e.g. Kerr, 1983).

In particular, premises that are highly visual for sighted persons are unlikely to be visualized by persons who are blind from birth, and thus, we predicted, should not hinder their reasoning, because they are able to construct spatial representations without being sidetracked by irrelevant visual images. In Knauff and May (2006) exactly this difference between sighted and congenitally totally blind individuals was found. We tested a group of sighted participants, a group of congenitally totally blind participants, and a group of blindfolded participants with normal vision. For both, the

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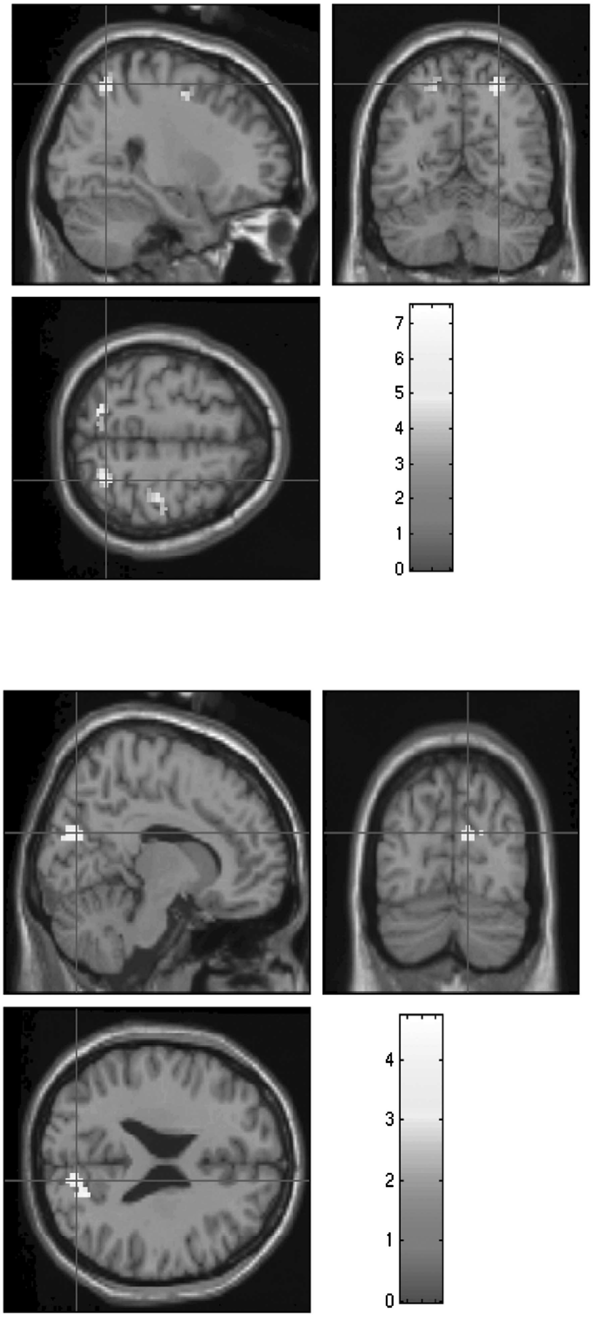


*Figure 3.* See caption on page 129.

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sighted and blindfolded participants, the visual premises significantly impeded the process of reasoning in terms of both accuracy and time needed to verify the conclusion. The participants who were blind from birth, however, were not affected by the ease with which the verbal relations could be visualized. They showed the same reasoning performance across all types of problems. Obviously, people who are blind from birth are *immune* to the visual-impedance effect, since they do not tend to construct disrupting visual images from the premises.

Further evidence for the account comes from a recent study on individual differences by Gazzo-Castaneda and Knauff (2008, Knauff & Gazzo-Castaneda, in prep). Bacon, Handley, and Newstead (2003, 2004) have presented evidence for individual differences in reasoning strategies, with most people seeming to represent and manipulate problem information using either a verbal or a visual strategy. In our study we used the well-known Verbalizer-Visualizer Questionnaire by Richardson (1977) to identify two groups of individuals with different cognitive styles. One group consisted of 11 individuals with a strong tendency towards visualization during thinking and the other group consisted of 11 people with a strong bias toward verbal thinking. The participants were selected on the basis of a pilot study with about 150 students, and this might be the reason why the study worked well, although the Verbalizer-Visualizer Questionnaire has many methodological problems (Antonietti & Giorgetti, 1998). In our study, the two groups had to solve relational reasoning problems that were easy to visualize (cutlery on a table) or difficult to visualize (with nonsense syllables). The interesting finding was that the visualizers showed a strong visual-impedance effect with the visual problems but not with non-visual problems. The verbalizers, in contrast, were not impaired by the visual problems (Knauff & Gazzo-Castaneda, in prep).

## 8. CONCLUSIONS AND IMPLICATIONS OF THE THEORY

I presented a neuro-cognitive theory of deductive relational reasoning with mental models and visual images. The theory is not spelled out in all details, and so far it also accounts only for reasoning with relations. Nev-

***Figure 3.*** (See artwork on page 128.) Images representing differentially activated brain areas during reasoning. The brain is again presented from the three different perspectives. The three images on the top show the typical foci of activation resulting from reasoning with spatial relations. The location of the highlighted areas indicates that the spatial information from reasoning problems is mapped to areas of the brain responsible for the multimodal integration of space from perception and working memory. The three images on the bottom show the activity in the back of the brain suggesting that individuals naturally construct visual images, if the reasoning problem is easy to visualize (from Knauff et al., 2003; see text for details).

ertheless, there is some evidence that other forms of reasoning also rely on mental models and that even more complex thinking succeeds without visual images although they are subjectively experienced. For instance, people often report representing mechanical systems and how they operate in visual mental images. Hegarty (2004) provides convincing evidence that this form of mechanical reasoning—although it is frequently accompanied by imagery—is also not a process of inspecting a holistic visual image in the "mind's eye." Instead, the "mental simulation" includes representations of nonvisible properties and is even more efficient with nonimagery processes and spatial representations (Hegarty, 2004). Given this converging evidence from different research areas, it would be very helpful if researchers in other areas of human thinking would also carefully distinguish between spatial and visual representations and processes. The present paper shows that such a distinction is indispensable to resolve many inconsistencies in the previous literature and to develop neuro-cognitively plausible theory of human reasoning with mental models and visual images.

Another interesting relation exists between the present attempt to explain human reasoning and the field of text-comprehension research. As mentioned previously, numerous studies have shown that visual representations are routinely activated during word and sentence comprehension. In fact, nowadays many scholars in reading research believe that mental imagery plays an essential role in the comprehension and reception of the text (e.g., Glenberg, 1997; Sadoski, 1985; Sadoski & Paivio, 1994; Stanfield & Zwaan, 2001; Zwaan, Stanfield, & Yaxley, 2002). The present account could challenge this widely shared assumption and might show that visual images can also hinder text comprehension. Some findings in this direction come, for example, from research on individuals with dyslexia (a reading deficit). Various studies have shown that one of the main causes for dyslexia seems to be the strong tendency of dyslexics to represent the information from a text in a visual, rather than a verbal, way (Károlyi et al., 2003). Davis (1997) argued that individuals with dyslexia are handicapped because they create a mental picture of narratives instead of possessing a verbal "inner monologue." Also pointing in this direction are neuroscience studies of reading, showing that dyslexic individuals process written information in an atypical way, frequently presenting activation in brain areas typically associated with visual, rather than language, processing (e.g., Grigorenko, 2001).

Psychological theories occasionally benefit when our introspective experiences agree with them. However, cognitive psychologists (and sometimes nonspecialists) know very well that such a coincidence can be fatally misguiding. Moreover, people typically do not distinguish between different types of introspections: representational states and cognitive operations (Barsalou, 1999). The aim of this article thus was to clarify the role of visual and spatial representations in reasoning and to develop a general theoretical framework for further research. One consequence from the reported findings is that

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individuals might not be aware of spatial representations during reasoning, or experience them as visual images, although they underlie our reasoning abilities. A second corollary is that visual imagery is *not* a mere epiphenomenon playing no causal role in reasoning (Pylyshyn, 1981, 2002; see also Knauff & Schlieder, 2005). It can (sometimes) be a nuisance because it impedes reasoning.

## AUTHOR NOTE

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