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FMRI-Evidence for a Three-Stage-Model of Deductive Reasoning

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Abstract

In an event-related fMRI study, we investigated the neuro-cognitive processes underlying deductive reasoning. We specifically focused on three temporally separable phases: (1) the premise processing phase, (2) the integration phase, and (3) the validation phase. We found distinct patterns of cortical activity during these phases, with initial temporo-occipital activation shifting to prefrontal and then parietal cortex during the reasoning process. Our findings demonstrate that human reasoning proceeds in separable phases, which are associated with distinct neuro-cognitive processes.

Introduction

Deductive reasoning starts with premises and yields a logically necessary conclusion that is not explicit in the premises. But what happens in the brain when we solve such deductive problems? Recent functional brain imaging studies have provided some first insights into the brain circuits underlying deductive reasoning. Reasoning with abstract premises seems to involve the right hemisphere, whereas reasoning with concrete material relies on processing in the left hemisphere (Goel, & Dolan, 2001; Goel, Büchel, Frith, & Dolan, 2000). During reasoning, portions of the parieto-occipital cortices are active, pointing to the role of visuo-spatial processes (Knauff, Mulack, Kassubek, Salih, & Greenlee, 2002; Knauff, Fangmeier, Ruff, & Johnson-Laird, 2003; Ruff, Knauff, Fangmeier, & Spreer, 2003). The more visual features are described in the reasoning problem, the more activity in occipital cortical areas can be found (Knauff, Fangmeier, Ruff, & Johnson-Laird, 2003). Moreover, reasoning-related activity in parietal areas correlates with visuo-spatial ability (Ruff, Knauff, Fangmeier, & Spreer, 2003).

However, most of these studies have one pitfall in common. They presented the problems as sentences, either on the screen or via headphones. This means that reasoning-related brain activity may have been confounded by higher-level linguistic processing. In addition, many of these studies examined the brain activation during the whole reasoning process in a blocked fashion, and thus could not distinguish reasoning-related processes during different stages of problem processing. Only a few study so far compared the neuronal processes during the crucial conclusion sentence of the reasoning problem with the presentation of irrelevant control sentences (e.g. Goel, & Dolan, 2001). However, these control sentences clearly did not need to be processed as elaborately as the reasoning problems and the study did not provide any information what happens during premises processing. Thus, it is unclear whether reasoning is associated with distinct sub-processes not related to sentence processing, and how these processes may be differentially involved in different stages of reasoning.

The aim of the present study was to disentangle the neuro-cognitive subprocesses underlying the different phases in the reasoning process, and at the same time to overcome the potential linguistic confound in the previous studies on the neuronal basis of deductive reasoning. We employed event-related functional magnetic resonance imaging with twelve participants, who solved (while in the scanner) 32 linear syllogisms (explanation below) with a spatial content. We decided to use problems with a spatial content, because spatial relations are easily understood by logically untrained participants. Since we aimed at distinguishing the pure reasoning process from the maintenance of information in working memory, in a second condition participants had to simply keep the premises of the identical problems in working memory (maintenance task) without making inferences (explanation below). Crucially, the premises and the conclusion of the inference problems were presented each as single display frames, by replacing the sentential premises with graphic arrangements describing the spatial relations between the letters V, X and Z. With this procedure no further linguistic processing was necessary to extract the spatial relations between the objects. Moreover, the processing of the first premise, the second premise and the conclusion was time-locked to the short presentation of the letter arrangements. Thus, we could examine the brain activity elicited by the different phases of the reasoning process. Based on behavioral findings concerning the cognitive processes involved in reasoning (Johnson-Laird, & Byrne, 1991; Evans, Newstead, & Byrne, 1993; Rader, & Sloutsky, 2002), we predicted that there should be different patterns of neuronal activation associated with *three phases* of the reasoning process: During the presentation of the first premise, reasoners have to process and keep in mind the two letters and their spatial relation (premise processing phase). During the second premise exclusively, the second premise together with the first premise must be integrated into one unified representation – a mental model – and a putative conclusion must be drawn (integration phase). Finally, reasoners compare the conclusion they drew from the putative model with the displayed conclusion, and indicate by pressing a button whether the displayed conclusion is "True" or "False" (validation phase). It is critical to appreciate that the processing of the matched maintenance problems also proceeded in three phases, but that participants only had to remember the premises and match it with the presented third sentence. They did not make any inferences. Although the different presentations thus cannot be called "premises" in the literal sense, we henceforth use the terms to clarify the correspondence to the reasoning problems. Prior to the problem presentation, a small letter was displayed, which identified the following problem as reasoning or maintenance problem. We hypothesized that the reasoning and the control maintenance task should both entail the maintenance of premises, but that only the reasoning problems should demand for the integration of the premises and the validation of a putative conclusion.

An event-related brain imaging study

Methods

Participants. Twelve right-handed male undergraduate and graduate students (mean age 22.4, *SD* 1.98) with normal or corrected-to-normal vision (contact lenses) gave their informed consent prior to their participation in the study. None of the volunteers had any history of neurological or psychiatric disorders, or of significant drug abuse. All procedures complied with both university and hospital ethical approval.

Materials. The materials consisted of 32 reasoning and 32 maintenance tasks. The reasoning problems contained two premises and a conclusion. 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

The letter of the premises and conclusions appeared sequentially on the screen. 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 premises it follows "V is to the left of Z" (conclusion). Participants used an MRI-compatible response box to indicate whether a conclusion was "True" or "False". The letter V, X, and Z were used, because they have almost the same black-white ratio and no task-related words (in German) can be build from them. 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. Here is an example for a maintenance task:

Premise 1:	V	X
Premise 2:	X	Z
Maintenance:	V	X

In this case, participants had to press the "TRUE" key, because the third sentence is an exact repetition of the first premise. Prior to each task a "S" or an "E" was presented for 1 sec to identify the next trial as reasoning problem ("Schließen" in German) or maintenance problem ("Erinnern" in German), respectively. The spatial relation between the two letters of each premise or conclusion was coded through placing it right or left from the midpoint of the screen. Each trial began with presentation of the first letter for 1500 ms, followed by the second letter for 1500 ms, and a pause for 1000 (first premise). The time period for the second premise and the conclusion or maintenance was the same as during the first premise. Each trial lasted for about 12 sec. In half of the premises and conclusions, the letter at the left side appeared first, followed by the letter on the right, while the other half were presented in the reverse order. This variation of term order is well-established in reasoning research, and prevented participants from anticipating the next letter and from drawing the conclusion during the second premise.

Behavioral data acquisition. Participants responded with index and middle finger on a response box in order to record the reaction time and accuracy of each task. Prior to the imaging study, participants were trained on 12 similar tasks outside the scanner to at least 75 % response accuracy.

Procedure and fMRI Data Acquisition. Problems were presented in an event-related design with four separate runs. Each run contained eight reasoning and eight recognition tasks in a pseudo-randomized order. All tasks were presented for an equal amount of time, and each premise or conclusion lasted for 4000 ms. Scanning was performed on a 1.5 T Siemens Vision scanner and the participant's head was fixed in the head coil. A mirror was placed on the coil so that participants could see a projection screen mounted on the rear of the scanner bore. All visual stimuli were projected onto this screen using a video projector. Further Information on the fMRI data preprocessing and the statistical analysis is provided as complementary materials under: *http://cognition.iig-uni.freiburg.de/team/members/fangmeier/download/md1_methods.pdf*.

Results

The behavioral data collected inside the scanner showed that reasoning problems were significantly more difficult than maintenance problems in terms of accuracy (91 % < 97% correct answers Z = 2.31, p = 0.021) and latency (3021 ms > 2843 ms response time Z = -2.04, p = 0.041, Wilcoxon-Test, because of non-normal distributions and inhomogeneity of variances, the non-parametric Wilcoxon-Test is appropriate for assessing the significance of differences in within-subjects experiments, Siegel, & Castellan, 1989).

The brain imaging data showed clearly distinguishable brain activation patterns during the three phases of deductive reasoning. First, as shown in Figure 1a, *the premise processing phase* (contrast second premise minus first premise) activated two large bilateral clusters of activation in the occipito-temporal cortex (OTC). Second, shown in Figure 1b, during the *integration phase* (contrast second premise minus conclusion) these two clusters in the OTC and an additional cluster in the anterior prefrontal cortex (APFC) were activated. The latter covered parts of the middle frontal (BA 10) and medial frontal gyrus (BA 32). Third, shown in Figure 1c, the *validation phase* (contrast conclusion minus second premise) activated three clusters, two in the prefrontal cortex (PFC) and one in the posterior parietal cortex. More precisely, the clusters in the PFC were located in the middle frontal gyrus (Brodmann Area BA 9, 8, and 6), extending into the medial frontal and the cingulate gyrus (BA 32) in the right hemisphere. The activation of the PPC covered parts of the precuneus (BA 7), and of the superior and inferior parietal lobule (BA 7, 40) in both hemispheres. The contrasts for the analysis of the maintenance task were calculated in a similar fashion as those for reasoning (all contrast are in parallel to the reasoning analyses). During the *premise processing phase*, we found slightly elevated activations in OTC as we had obtained during reasoning (compare Fig. 1a with 2a). However, overall in this phase the patterns of activation were quite similar. During presentation of the second premise (premise maintenance phase), which now required only premise maintenance but not integration, we again found similar OTC activation, but significantly lower APFC activation (compare Figure 1b with 2b). A region of interest (ROI) analysis of the mean activity in these clusters confirmed that the APFC activity elicited by the processing of the second premise was higher during reasoning than during the maintenance task (analysis of variance [ANOVA] interaction Task x Phase: $F(2,22) = 7.066$; $p \leq 0.01$, one-tailed t-test: $t(11) = 3.995$; $p \leq 0.01$), while the mean signal in the OTC clusters did not differ. Finally, during of the third phase of the maintenance problem (recognition of premises), there were significantly lower PFC activations, and less extensive right PPC activation than during the reasoning problems (compare Fig. 1c with 2c), as confirmed by the significant differences in ROI analyses in these clusters (PFC: ANOVA interaction Task x Phase: $F(2,22) = 6.551$; $p \leq 0.01$, one-tailed t-test: $t(11) = 2.738$; $p \leq 0.05$, PPC: ANOVA interaction Task x Phase: $F(2,22) = 6.227$; $p \leq 0.01$, one-tailed t-test $t(11) = 2.183$; $p \leq 0.1$). For further information concerning Tailarach coordinates, Z-scores, beta-values, etc., please visit the complementary materials on the above mentioned web-page or have a look into Fangmeier et al. (2005).

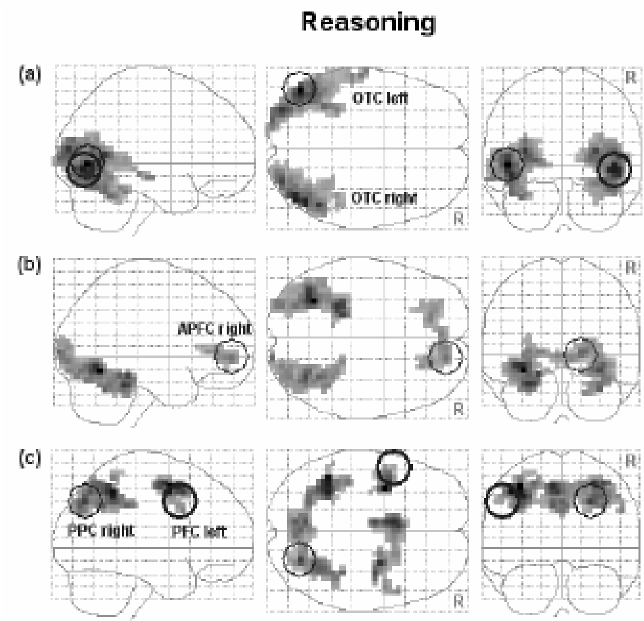

Figure 1. Brain activation during reasoning. The clusters in the glass brain for the reasoning tasks (a) premise processing phase, (b) integration phase, (c) validation phase. The activations were significant at the cluster level calculated with SPM99 ($p \leq 0.05$, corrected, threshold t = 3.0). Circles around parts of the clusters mark the five selections of voxels (+/- 12 mm) for the ROI analyses (ANOVA repeated measurements, 2x3 factorial design).

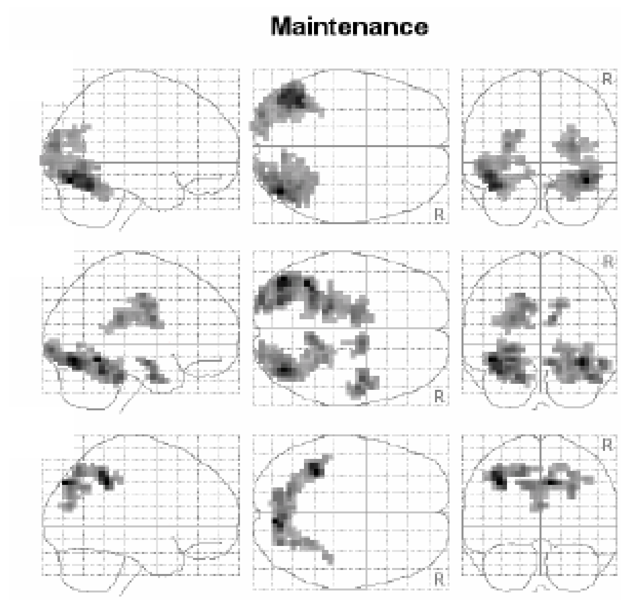

Figure 2. Brain activation during the maintenance tasks. The clusters in the glass brain for the maintenance tasks (a) premise processing phase, (b) premise maintenance phase, (c) validation phase. For more details see legend to Figure 1.

Discussion

The fundamental result of our study is that different cortical structures are activated during different phases of deductive thinking. Elevated activation of occipito-temporal structures was found in the premise processing phase, activation in the anterior prefrontal cortex in the integration phase, and activation of the posterior parietal and prefrontal cortex during the reasoning validation phase. Because problems were presented as graphic depictions of the state of the affairs, these distinguishable activations cannot be explained by reading and linguistic processing of the premises. Moreover, the maintenance condition employed in the present study was identical in terms of problem content and visual display to the reasoning problems. In this condition, the APFC activation was significantly lower in the premise integration phase, and the PFC activation significantly lower in the maintenance validation phase.

Our data show that some neural structures are unique to the reasoning process, others are more involved in reasoning than in maintenance, and yet others are involved in both reasoning and premise maintenance. Although this is a clear pattern of results, there are also some ambiguities in the present data. The differences between reasoning and working memory tasks, for instance, could be due to performance difficulty, because during performing working memory tasks the participants showed higher accuracy and faster reaction times than during reasoning tasks. To rule out this explanation we computed an additional analysis in which we added the response times as an additional parametric factor in the SPM model. In this way we could partial out the difficulty factor. No critical differences to the present findings were found.

A second question is related to individual differences. In a previous study, we scanned the brain activity of our participants during reasoning and also measured their visuo-spatial ability with a well-known subset of tasks from an intelligence inventory. Interestingly, the brain activation was significantly modulated by the participants' visuo-spatial skill. The higher the participants' visuo-spatial skill, the better their reasoning performance, and the less activation was present in visual association areas during reasoning (Ruff, Knauff, Fangmeier & Spreer, 2003). We now computed a similar analysis based on the present findings. To examine the influence of individual differences, the participants were tested after the experiment with the "Block Design Test" of the German equivalent to the Wechsler Adult Intelligence Scale (HAWIE-R, Tewes, 1991). We correlated the beta values for each reasoning phase and cluster with the outcome of the Block Design Test (BDT) for each participant. The results showed that performance on the BDT correlated with the accuracy of the reasoning tasks, although this correlation was not significant. In the BDT-Activation-correlation we found positive correlations during the validation phase in the APFC and the PPC. We also found negative correlations during the integration phase in the PPC. These findings shed new light on our previous findings, because they show that the correlations systematically vary over the different reasoning phases. These findings and the results concerning difficulty factors are extensively discussed in Fangmeier, Knauff, Ruff, and Sloutsky (2005).

The third problematic point is related to the experimental setup of our study. One could object that the identification of three different phases is not so surprising, because the experiment was set up to ensure 3 stages. Although this is true, we believe that this is one of the main advantages of our study. As everybody knows there is a many to many mapping between cortical regions and cognitive functions, and thus 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. To study the neural correlates of high-level cognition, therefore very specific hypothesis must be formulated and the design of such studies must be strongly guided by what is known from behavioral studies. The study reported here is in the spirit of this connection between neural activation ad behavioral findings, because the three phases of reasoning are a solid result from many cognitive experiments (cf. Johnson-Laird, & Byrne, 1991; Evans, Newstead, & Byrne, 1993; Manktelow, 1999).

Given this overlap between the two classes of findings we here propose a *neuro-cognitive three-stage model of human (relational) reasoning*. In Knauff (2005) this model is described in more detail and proved by many behavioral findings.

The *premise processing phase* is related to bilateral cortical structures in the occipito-temporal cortex (OTC). These areas are involved in visual working memory (Toga, & Mazziotta, 2000; Postle, Stern, Rosen, & Corkin, 2000; Courtney, Ungerleider, Keil, & Haxby, 1996; Kosslyn, Alpert, Thompson, Chabris, Rauch, et al., 1994) and imagery (Kosslyn, Ganis, & Thompson, 2001), and correspond to the ventral "what"-stream (Ungerleider, Courtney, & Haxby, 1998). This is consistent with the notion that reasoners use their general knowledge to construct a visuo-spatial model of the "state of the affairs" that the premises describe (Johnson-Laird, & Byrne, 1991). It also agrees with the finding that reasoning with materials that are easy to visualize leads to activity in the visual association cortex (Goel, Buchel, Frith, & Dolan, 2000; Knauff, Mulack, Kassubek, Salih, & Greenlee, 2002; Knauff, Fangmeier, Ruff, & Johnson-Laird, 2003; Ruff, Knauff, Fangmeier, & Spreer, 2003). However, in contrast to previous studies these visuo-spatial processes can now be linked to specific phases of the reasoning process, namely the first (and second phase, see below) of reasoning. It is critical to see that in this phase there was no significant difference between reasoning and maintenance, demonstrating the premises are similarly processed under both conditions. Thus, these processes are not specific to reasoning, but primarily related to working memory.

In the *integration phase* reasoners construct a single integrated model of the state of affairs described in the premises, so that the premises of the reasoning problem are no longer represented as separate entities in working memory (as assumed by rule-based theories of reasoning; Rips, 1994; Braine, & O'Brien, 1998). From this model a putative conclusion can be drawn. The activation of the APFC and the anterior cingulate cortex during this stage of the reasoning process supports this assumption of premise integration, as the APFC has been found to be specifically involved in relational integration during reasoning, or in considering multiple relations simultaneously (Waltz, Knowlton, Holyoak, Boone, Mishkin, et al., 1999; Prabhakaran, Narayanan, Zhao, & Gabrieli, 2000; Christoff, Prabhakaran, Dorfman, Zhao, Kroger, et al., 2001). Note also that crucially, such integration processes are not necessary during pure maintenance problems, for which we found significantly lower APFC activation during the premise maintenance phase.

In the *validation phase* the putative conclusion must be verified. Here we found activations in the right PPC and the bilaterial PFC, which were more marked for the reasoning than for the maintenance tasks. The PPC plays a crucial role in spatial processing and working memory (Baker, Frith, Frackowiak, & Dolan, 1996; Oliveri, Turriziani, Carlesimo, Koch, Tomaiuolo, et al., 2001; Postle, Berger, & D'Esposito, 1999; Smith, Jonides, Marshuetz, & Koeppe, 1998; Burgess, Maguire, Spiers, & O'Keefe, 2001) and in the integration of sensory information from all modalities into egocentric spatial representations (Andersen, Snyder, Bradley, & Xing, 1997; Bushara, Weeks, Ishii, Catalan, Tian, et al., 1999; Colby, & Duhamel, 1996; Xing, & Andersen, 2000). Our finding thus highlights the critical role of modality-independent spatial representations specifically during the validation of the premises.

Note that this account also resolves inconsistencies in previous neuroimaging 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 often shown concurrent activation of visual association cortices (Goel, & Dolan, 2001; Goel, Buchel, Frith, & Dolan, 2000), which points to the role of "visual mental imagery" in reasoning (Ruff, Knauff, Fangmeier, & Spreer, 2003). The present study unifies these accounts, since it shows for the first time that visual association areas are indeed involved in premise processing and the construction of an initial static representation of the initial model, but that more abstract spatial representations held in parietal cortices are crucial for subsequent processes, in particular when the model must be verified. The supplementary activation in the dorsolateral prefrontal cortex (DLPFC, BA 9 left hemisphere) in association with the dorsal anterior cingulate cortex (ACC) during validation of the conclusion indicates that further executive processes are exclusively devoted to the control of this validation of spatial mental models (Smith, & Jonides, 1999; Fletcher, & Henson, 2001).

Conclusion

In sum, our study on the neuro-cognitive processes underlying reasoning supports the notion that reasoning can be described as a three-stage process, reflecting premise processing, integration, and validation. For all these phases we identified the corresponding neural structures. The two latter phases are specific to reasoning, and they resulted in higher activation of anterior frontal, as well as the prefrontal and right posterior parietal cortices, respectively.

Our three-stage model of the neural correlates of reasoning is strongly related to a strictly cognitive framework of human reasoning (Johnson-Laird, 2001). This so-called "mental models theory" relies on behavioral data only, but also assumes that reasoners construct visuo-spatial mental models, derive a putative conclusion from them, and try to validate this conclusion by searching for counter-examples contradicting this conclusion (Johnson-Laird, 2001). Our present study provides neurophysiological support for such three distinct phases of reasoning, at least for deductive reasoning with spatial relations. Since the theory of mental models claims to be a universal theory of human reasoning, these three phases should underlie all other sorts of reasoning as well, e.g., syllogistic reasoning with quantifiers such as "all" "some", "none", or conditional reasoning with "if" and "than". A word of caution, however, is that the cognitive and neural processes in reasoning might depend on the nature of the problem. Reasoning with visually presented spatial relations might elicit mental models, but reasoning with other problems might elicit other representations and processes.

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References

Andersen, R. A., Snyder, L. H., Bradley, D. C., & Xing, J. (1997). Multimodal representation of space in the posterior parietal cortex and its use in planning movements. *Annual Review of Neuroscience*, 20, 303-30.

Baker, S. C., Frith, C. D., Frackowiak, R. S., & Dolan, R. J. (1996). Active representation of shape and spatial location in man. *Cerebral Cortex*, 6 (4), 612-9.

Braine, M. D. S., & O'Brien, D. P. (1998). *Mental logic*. Mahwah (NJ): Erlbaum.

Burgess, N., Maguire, E. A., Spiers, H. J., & O'Keefe, J. (2001). A temporoparietal and prefrontal network for retrieving the spatial context of lifelike events. *Neuroimage*, 14 (2), 439-53.

Bushara, K. O., Weeks, R. A., Ishii, K., Catalan, M. J., Tian, B., et al. (1999). Modality-specific frontal and parietal areas for auditory and visual spatial localization in humans. *Nature Neuroscience*, 2 (8), 759-66.

Christoff, K., Prabhakaran, V., Dorfman, J., Zhao, Z., Kroger, J. K., et al. (2001). Rostrolateral prefrontal cortex involvement in relational integration during reasoning. *Neuroimage*, 14 (5), 1136-49.

Colby, C. L., & Duhamel, J. R. (1996). Spatial representations for action in parietal cortex. *Cognitive Brain Research,* 5 (1-2), 105-15.

Courtney, S. M., Ungerleider, L. G., Keil, K., & Haxby, J. V. (1996). Object and spatial visual working memory activate separate neural systems in human cortex. *Cerebral Cortex*, 6 (1), 39-49.

Evans, J. S. B. T., Newstead, S. E., & Byrne, R. M. J. (1993). Human reasoning: The psychology of deduction. Hillsdale, NJ, England: Lawrence Erlbaum Associates, Inc.

Fangmeier, T., Knauff, M., Ruff, C. C., & Sloutsky V. (2005). The neural correlates of logical thinking: fMRI evidence for a three-stage model of deductive reasoning. *Journal of Cognitive Neuroscience, under revision.*

Fletcher, P. C., & Henson, R. N. (2001). Frontal lobes and human memory: insights from functional neuroimaging. *Brain*, 124 (Pt 5), 849-81.

Goel, V., & Dolan, R. J. (2001). Functional neuroanatomy of three-term relational reasoning. *Neuropsychologia*, 39 (9), 901-9.

Goel, V., Buchel, C., Frith, C., & Dolan, R. J. (2000). Dissociation of mechanisms underlying syllogistic reasoning. *Neuroimage*, 12 (5), 504-14.

Johnson-Laird, P. N. (2001). Mental models and deduction. *Trends in Cognitive Sciences*, 5 (10), 434-442.

Johnson-Laird, P. N., & Byrne, R. M. J. (1991). *Deduction*. Hove (UK): Erlbaum.

Knauff, M (in press). A three-stage theory of relational reasoning with mental models and visual images. In Held, C., Knauff, M., & Vosgerau, G (Eds.), *Mental Models in Cognitive Psychology, Neuroscience and Philosophy*. North-Holland: Elsevier.

Knauff, M., Fangmeier, T., Ruff, C. C., & Johnson-Laird, P. N. (2003). Reasoning, models, and images: behavioral measures and cortical activity. *Journal of Cognitive Neuroscience*, 15 (4), 559-73.

Knauff, M., Mulack, T., Kassubek, J., Salih, H. R., & Greenlee, M. W. (2002). Spatial imagery in deductive reasoning: a functional MRI study. *Cognitive Brain Research*, 13 (2), 203-12.

Knauff, M., Rauh, R., Schlieder, C., & Strube, G. (1998). Mental models in spatial reasoning. In Freksa, C., Habel, C., & Wender, K. F. (Ed.), *Spatial cognition - an interdisciplinary approach to representation and processing of spatial knowledge* (pp. 267 - 291). Berlin: Springer-Verlag.

Kosslyn, S. M., Alpert, N. M., Thompson, W. L., Chabris, C. F., Rauch, S. L., et al. (1994). Identifying objects seen from different viewpoints. A PET investigation. *Brain*, 117 (Pt 5), 1055-71.

Kosslyn, S. M., Ganis, G., & Thompson, W. L. (2001). Neural foundations of imagery. *Nature Reviews Neuroscience*, 2 (9), 635-42.

Manktelow, K. (1999). *Reasoning and thinking*. Hove (UK): Psychology Press.

Oliveri, M., Turriziani, P., Carlesimo, G. A., Koch, G., Tomaiuolo, F., et al. (2001). Parieto-frontal interactions in visual-object and visual-spatial working memory: evidence from transcranial magnetic stimulation. *Cerebral Cortex*, 11 (7), 606-18.

Postle, B. R., Berger, J. S., & D'Esposito, M. (1999). Functional neuroanatomical double dissociation of mnemonic and executive control processes contributing to working memory performance. *Proceedings of the National Academy of Sciences,* U.S.A, 96 (22), 12959-64.

Postle, B. R., Stern, C. E., Rosen, B. R., & Corkin, S. (2000). An fMRI investigation of cortical contributions to spatial and nonspatial visual working memory. *Neuroimage*, 11, 409-23.

Prabhakaran, V., Narayanan, K., Zhao, Z., & Gabrieli, J. D. (2000). Integration of diverse information in working memory within the frontal lobe. *Nature Neuroscience*, 3 (1), 85-90.

Presentation ® [computer software] (2003). Albany (USA, CA): Neurobehavioral Systems.

Rader, A. W., & Sloutsky, V. M. (2002). Processing of logically valid and logically invalid conditional inferences in discourse comprehension. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, 28 (1), 59-68.

Rips, L. J. (1994). *The psychology of proof:* Cambridge, MA, US: The MIT Press.

Ruff, C. C., Knauff, M., Fangmeier, T., & Spreer, J. (2003). Reasoning and working memory: common and distinct neuronal processes. *Neuropsychologia*, 41 (9), 1241-53.

SPM99 [computer software] (1999). London (UK): Wellcome Department of Cognitive Neurology.

Siegel, S., & Castellan, N. J. (1989). *Nonparametric statistics for the behavioral sciences.* New York u.a.: McGraw-Hill.

Smith, E. E., & Jonides, J. (1999). Storage and executive processes in the frontal lobes. *Science*, 283 (5408), 1657-61.

Smith, E. E., Jonides, J., Marshuetz, C., & Koeppe, R. A. (1998). Components of verbal working memory: evidence from neuroimaging. *Proceedings of the National Academy of Sciences,* U.S.A, 95 (3), 876-82.

Tewes R. (1991). Hamburg-Wechsler-Intelligenztest für Erwachsene [German version of the HAWIE-R]. Göttingen: Hogrefe.

Toga, A. W., & Mazziotta, J. C. (2000). *Brain mapping: The Systems*. San Diego: Academic Press.

Ungerleider, L. G., Courtney, S. M., & Haxby, J. V. (1998). A neural system for human visual working memory. *Proceedings of the National Academy of Sciences*, U.S.A, 95 (3), 883-90.

Waltz, J. A., Knowlton, B. J., Holyoak, K. J., Boone, K. B., Mishkin, F. S., et al. (1999). A System for Relational Reasoning in Human Prefrontal Cortex. *Psychological Science* (10), 119-25.

Xing, J., & Andersen, R. A. (2000). Models of the posterior parietal cortex which perform multimodal integration and represent space in several coordinate frames. *Journal of Cognitive Neuroscience,* 12 (4), 601-14.