Reasoning and the *Visual-Impedance* Hypothesis

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Abstract. The *visual-impedance* hypothesis postulates that relational expressions which elicit visual images without a spatial component impede reasoning (Knauff and Johnson-Laird, in press). The goal of the present article is to summarize some experimental findings that support this hypothesis. Previous studies yielded four sorts of relations: (1) visuo-spatial relations, such as "above-below", that are easy to envisage visually and spatially, (2) visual relations, such as "cleaner-dirtier" that are easy to envisage visually but hard to envisage spatially, (3) spatial relations, such as "ancestor of-descendant of", that are hard to envisage visually but easy to envisage spatially and (4) control relations, such as "better-worse", that are hard to envisage either visually or spatially. Two behavioral studies showed that visual relations slow down reasoning in comparison with control relations, whereas visuo-spatial and spatial relations yield inferences comparable to those of control relations. The results of an fMRI study showed that in the absence of any correlated visual input (problems were presented acoustically via headphones) reasoning about all four sorts of relations evoked activity in the left middle temporal gyrus, in the right superior parietal cortex, and bilaterally in the precuneus. However, only the visual relations also activated areas of the primary visual cortex corresponding to Brodmann's area 18 (V2). The findings corroborate the theory that individuals rely on mental models for deductive reasoning, and that visual imagery irrelevant to reasoning impedes the process.

1 Introduction

Images are an important part of human cognition and it is natural to suppose that they can help humans to reason. This view is supported by various sorts of evidence including the well-known studies of the mental rotation and the mental scanning of images (Shepard and Cooper, 1982; Kosslyn, 1980). Moreover, several studies have shown that reasoning depends on the ease of imagining the premises, the instructions to form images, and the participants' ability to form images (e.g., Shaver, Pierson, and Lang, 1976; Clement and Falmagne, 1986). In contrast, however, other studies have failed to detect any effect of imageability on reasoning. Sternberg (1980) found no difference between the accuracy of solving problems that were easy or hard to visualize. Richardson (1987) reported that reasoning with visually concrete problems was no better than reasoning with abstract problems. Johnson-Laird, Byrne and Tabossi

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(1989) examined reasoning with three transitive relations that differed in imageability: *equal in height, in the same place as,* and *related to* (in the sense of kinship). They did not find any effect of imageability on reasoning accuracy. Newstead, Pollard, and Griggs (1986) had reported similar results. In Knauff (2001), Knauff and Johnson-Laird (2000), and Knauff and Johnson-Laird (in press) we postulated that a possible resolution of the inconsistency in the results is that investigators have overlooked the distinction between *visual images* and *spatial representations*. We formulated the following *hypothesis:*

> *Visual-impedance* hypothesis*:* Relations that elicit visual images without a component relevant to inference impede the process of reasoning.

The distinction between visual and spatial processes was originally detected in lesion studies with monkeys (Ungerleider and Mishkin, 1982) and in experiments with humans with brain injuries (for a review, see Newcombe and Ratcliff, 1989). These studies showed that visual and spatial processes are associated with different cortical areas. Additional support for the distinction comes from experiments examining human working memory (e.g. Logie, 1995) and most recently from functional brain imaging studies (e.g. D'Esposito, 1998; Smith, et al, 1995).

But, what does the distinction between visual and spatial imagery mean for reasoning? And how can the *visual-impedance* hypothesis be justified? On the one hand, a relation such as: *The hat is above the cup,* is easy to visualize given a modicum of competence in forming images. However, it can also be readily represented spatially. That is, individuals can construct a spatial model of the relation without any conscious awareness of a visual image. According to the theory of mental models, such a model suffices for reasoning. It captures the relevant logical properties. Hence, the transitivity of a relation of the form: *A is above B*, derives merely from the meaning of the relation and its contribution to models of assertions. Given premises of the form:

A is above B.
B is above C.

Reasoners build a two- or three-dimensional mental model that satisfies the premises:

A
B
C

This model supports the conclusion: *A is above C,* and no model of the premises refutes this conclusion (see Johnson-Laird and Byrne, 1991). Mental models are therefore not to be identified with visual images. Models are abstract, but they make it possible in certain cases to construct a visual image from a particular point of view (see e.g. Johnson-Laird, 1998).

On the other hand, a relation such as: *The hat is dirtier than the cup,* is easy to visualize, but it seems much less likely to be represented spatially. Subjectively, one seems to form an image of a dirty hat and an image of a less dirty cup. Such an image contains a large amount of information that is irrelevant to the inference, and so it puts an unnecessary load on working memory. In addition, reasoners have to isolate the information that is relevant to the inference. And so they might be side-tracked by the irrelevant visual details. A visual image of, say, a dirty hat and a dirty cup gets in the way of forming a representation that makes the transitive inference possible.

In the next section, we summarize two behavioral experiments that test the *visual-impedance* hypothesis. We then present some results from an fMRI study on imageability and reasoning. For the benefit of the interdisciplinary readership of the present book, we refrain from reporting experimental details, and we discuss only those results that are statistically reliable (for further details, see Knauff, Fangmeier, Ruff, and Johnson-Laird, 2002 and Knauff and Johnson-Laird, in press).

2 Behavioral Experiments

The aim of the experiments is was to test the *visual-impedance* hypothesis. In Experiment 1, we examined reasoning with three sorts of relations:

1. Visuo-spatial relations that are easy to envisage visually and spatially (*above* and *below*, *in front of* and *to the back of*).
2. Visual relations that are easy to envisage visually but hard to envisage spatially (*cleaner* and *dirtier*, *fatter* and *thinner*)
3. Control relations that are hard to envisage both visually and spatially (*better* and *worse*, *smarter* and *dumber*).

The relations were selected from those in a study in which students from Princeton University rated the ease of envisaging a set of relations as visual images and as spatial layouts (Knauff and Johnson-Laird, 2000). In this study, we had examined the three types of relations in transitive inferences (Knauff and Johnson-Laird, 2000). However, it is possible that such inferences favor certain reasoning strategies. Hence, in the present experiment we examined the three sorts of relations in reasoning that combined conditional and relational reasoning. If our *visual-impedance* hypothesis is correct, then visual relations will slow down reasoning in comparison with the visuo-spatial and control relations. But, if the orthodox imagery hypothesis is correct, then participants should perform better with visual relations. We also manipulated the difficulty of the inferences.

The participants had to evaluate conditional inferences in the form of modus ponens, e.g.:

If the ape is smarter than the cat, then the cat is smarter than the dog.
The ape is smarter than the cat.
Does it follow:
The ape is smarter than the dog?

All the inferences used the same nouns (*dog*, *cat*, *ape*) in order to minimize differences as a result of anything other than the relations. The difficulty of the inferences was manipulated by using converse relations. The easiest inferences were of the form exemplified in the preceding example:

1. If aRb then bRc
aRb
aRc?

where *aRb* denotes a proposition asserting that a transitive relation, *R*, holds between two entities, *a* and *b*. The converse relation, *R'*, such as *dumber*, yields more difficult inferences in the following forms:

2.	If aRb then cR'b aRb aRc?	3.	If bR'a then bRc bR'a aRc?

Reasoners now have to convert cR'b in order to make the transitive inference.The hardest form of inference used two separate converse relations, one in the premise and one in the conclusion:

4. If bR'a then bRc
   bR'a
   cR'a?

The participants acted as their own controls and evaluated two valid and two invalid inferences at the three levels of difficulty for each of the three sorts of relations (visual, visuo-spatial, control), making a total of 36 problems.

Overall, the participants made 71% correct responses. The trend concerning the effect of the converse relations on the percentages of correct responses fell short of significance: The easiest problems (Type 1) yielded 86% correct responses with a mean latency of 2.6s, the intermediate problems with one converse relation (Types 2 and 3) yielded 73% correct responses with a mean latency of 2.7s, and the hardest problems (Type 4) yielded 54% correct problems with a mean latency of 3.3s (Page's $L = 243$, $p > .05$, and $L = 242$, $p > .05$, respectively). There was no significant difference in accuracy for the three sorts of relations at any level of difficulty, and there was no significant interaction between the two variables. Likewise, the three sorts of relations did not have a significant effect on accuracy at any level of difficulty, and there was no significant interaction between the two variables (Wilcoxon test, $z = 0.58$, $p > .56$).

In contrast to the results on accuracy, the latencies of the responses corroborated the *visual-impedance* hypothesis. Figure 1 presents the mean latencies for the correct responses to the inferences based on the three sorts of relations. There was a reliable trend: Responses were faster to the visuo-spatial inferences (2456 ms) than to the control inferences (2643 ms), which in turn were faster than the visual inferences (3365 ms; Page's $L = 255$, $p < .05$). The difference between the visuo-spatial inferences and the control inferences was not significant, but the control inferences were reliably faster than the visual inferences (Wilcoxon test $z = 2.46$; $p < .02$). There was no reliable interaction between the relations and the levels of difficulty in their effects on latencies (Wilcoxon test, $z = 0.75$, $p > .45$).

These results show that the visual relations slowed down reasoning in comparison with control relations, which were harder to visualize. There was a tendency, though it was not significant, for the visuo-spatial relations to yield slightly faster responses than the control relations.

What happens if a relation is easy to envisage spatially but not easy to visualize? Our previous rating studies failed to discover any such relations. But, if materials that are easy to visualize impair reasoning, whereas materials that are easy to envisage spatially speed up reasoning, then reasoning based on purely spatial relations should be the fastest.

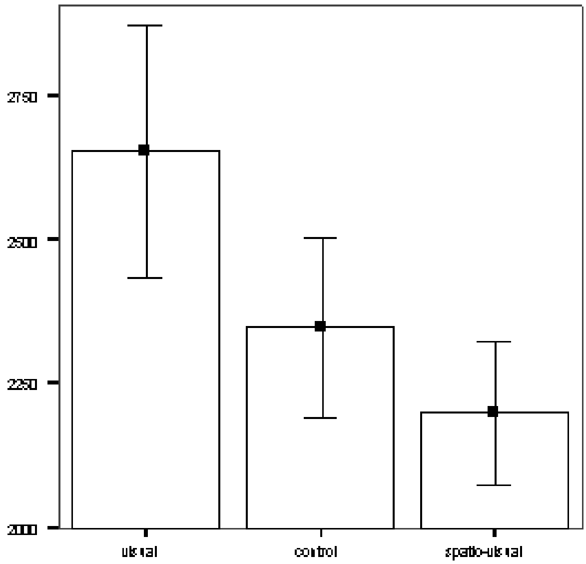

Fig. 1. Mean response latencies [in ms] and standard errors in reasoning in Experiment 1 with three sorts of relations: visual relations, control relations and visuo-spatial relations.

We therefore renewed our search for such relations. We asked twelve native German speakers at Freiburg University to complete a questionnaire in which they rated the ease of forming visual images and spatial layouts for a set of relational assertions. We included the relations from the first rating study but added more relations, which seemed easy to envisage spatially but difficult to visualize (*earlier* and *later*, *older* and *younger*, *hotter* and *colder*, *faster* and *slower*, *further North* and *further South*, *stronger* and *weaker*, *bigger* and *smaller*, *ancestor of* and *descendent of*, and *heavier* and *lighter*). The results replicated those from the earlier study at Princeton University and yielded the same three sorts of relations. We concluded that the procedure of separate ratings might not be sensitive enough to reveal purely spatial relations. We therefore carried out a study using a different procedure.

The participants rated each relation on a single bipolar seven-point scale, ranging from ease of evoking a "visual" image at one end of the scale to ease of evoking a "spatial" layout at the other end of the scale. The instructions stated that a visual representation is a vivid visual image that can include people, objects, colors, and shapes, and that it can be similar to a real perception. They stated that a spatial representation is a more abstract layout and represents something on a scale or axis, or in a spatial array. We tested 20 students with a set of 35 relations.

The results revealed two pairs of purely spatial relations: *ancestor of* and *descendant of*, and *further North* and *further South* (in German, *nördlicher* and *südlicher*, which are single words). The ratings for the four sorts of relations differed significantly (Friedman analysis of variance $F = 38.33$; $p < .001$). With these relations, we carried out a second experiment.

Experiment 2 examined reasoning with the four sorts of relations (visual, spatial, visuo-spatial, and controls). The *visual-impedance* hypothesis predicts that the visual relations should slow down reasoning. If the construction of a spatial representation speeds up reasoning, even in the absence of visualization, then both the spatial and the visuo-spatial relations should speed up reasoning in comparison with the control relations. Hence, the four relations should show the following trend in increasing latencies for reading and reasoning: spatial, visuo-spatial, control, and visual.

The materials consisted of 16 three-term and 16 four-term series inferences. All the inferences again used the same nouns (*dog*, *cat*, *ape*, and for four-term inferences: *bird*). Here is an example of a three-term inference with a valid conclusion:

The dog is cleaner than the cat.
The ape is dirtier than the cat.
Does it follow that:
The dog is cleaner than the ape?

And here is an example of a four-term series inference with an invalid conclusion:

The ape is smarter than the cat.
The cat is smarter than the dog.
The bird is dumber than the dog.
Does it follow that:
The bird is smarter than the ape?

There were two valid and two invalid inferences using each of the four sorts of relations in both three-term and four-term series inferences, making a total of 32 inferences. The 24 participants acted as their own controls and evaluated the 32 inferences presented in random order.

Overall, the participants responded correctly to 74% of the inferences and there was no significant difference in error rates for the different sorts of inferences. The mean latencies for the correct responses to the four sorts of relations are shown in Figure 2. The fastest response was for the spatial relations (3516ms), followed by the visuo-spatial relations (3736ms), the control relations (3814ms), and the visual relations (4482ms). This trend was statistically significant (Page's $L = 648$, $z=3.40$, $p < .05$). However, as Figure 2 suggests, the only significant effect is that visual relations slow down reasoning to a greater extent than the other three relations (Wilcoxon test $z = 2.46$; $p < .015$).

The first experiment showed that visual relations significantly impeded the process of reasoning, whereas visuo-spatial relations yielded response latencies comparable to those of control relations. The second experiment showed that purely spatial relations, which are difficult to envisage visually but easy to envisage spatially, yield slightly faster inferences, though the trend was not reliable. In both experiments, however, visual relations impeded reasoning.

Some accounts of reasoning postulate that inferences are based on visual images, which are similar in structure to actual percepts, and which can represent colors, shapes, and spatial extent. Images can be rotated and scanned, and they have a limited resolution (Kosslyn, 1980). Mental operations on an image can be isomorphic to those on real percepts. Similarly, an image can be confused in memory with a real percept (Johnson and Raye, 1981). Reasoning based on images calls for individuals to “look” at the image based on the premises, and to "read off" a conclusion not explicitly stated in the premises. This account of reasoning has difficulty in explaining our results. If reasoning is based on visual images, then it is hard to understand why the visual relations in our studies slowed down reasoning performance.

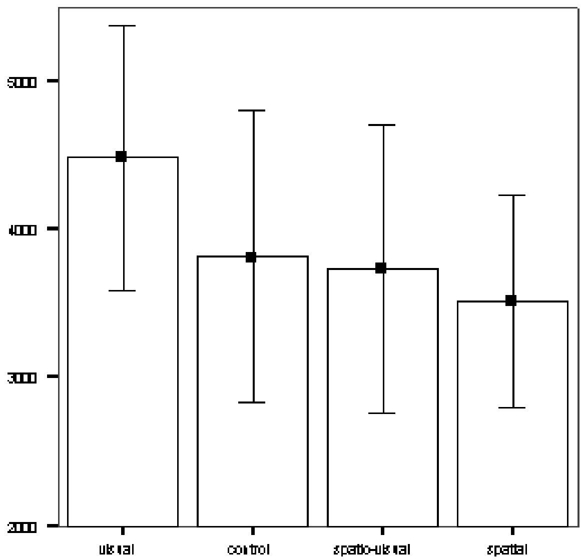

Fig. 2. Mean response latencies [in ms] and standard errors in relational reasoning with four sorts of relations: visual relations, control relations, visuo-spatial relations, and spatial relations.

What our results suggest is that in many cases reasoning is based not on visual images, but on more abstract structures, i.e., mental models. These representations avoid excessive visual detail in order to bring out salient information for inferences (Johnson-Laird, 1983; Johnson-Laird and Byrne, 1991).

3 A Functional Brain Imaging Experiment

We have performed several recent studies of reasoning and visual imagery using functional magnetic resonance imaging (fMRI). In a study by Knauff, Mulack, Kassubek, Salih, and Greenlee (2002), for instance, conditional and relational reasoning activated a bilateral parietal-frontal network distributed over parts of the prefrontal cortex, the inferior and superior parietal cortex, and the precuneus, whereas no significant activation occurred in the occipital cortex, which is usually activated by visual imagery (Kosslyn et al., 1993; Kosslyn et al., 1999; Kosslyn, Thompson, andAlpert, 1997; Sabbah et al., 1995; a contrasting result is reported in Knauff, Kassubek, Mulack, and Greenlee, 2000). In fact, reasoning activated regions of the brain that make up the “where-pathway” of spatial perception and working memory (e.g., Ungerleider and Mishkin, 1982; Smith et al., 1995). In contrast, the “what-pathway” that processes visual features such as shape, texture, and color (cf. also Landau and Jackendoff, 1993; Rueckl, Cave, and Kosslyn, 1989; Ungerleider, 1996) seemed not to be activated. Other experiments have corroborated these findings. Prabhakaran, Smith, Desmond, Glover, and Gabrieli (1997) studied Raven's Progressive Matrices and found (for inductive reasoning) increased activity in right frontal and bilateral parietal regions. Osherson et al. (1998) compared inductive and deductive reasoning and found that the latter increased activation in right-hemisphere parietal regions. Goel and Dolan (2001) studied concrete and abstract three-term relational reasoning and found activation in a parietal-occipital-frontal network. Kroger, Cohen, and Johnson-Laird (2001) found that reasoning in contrast to mental arithmetic based on the same assertions activated right frontal areas often associated with spatial representation.

What happens in the brain if participants solve problems with the four sorts of relations from the behavioral experiments (visual, visuo-spatial, spatial, and control)? Are the differences in imageability reflected in differences in brain activation? The behavioral experiments showed that reasoning with visual relations was more difficult than with the other relations, but there was no significant difference between visuo-spatial, spatial, and control problems. The *visual-impedance* effect appears to occur because visual details are irrelevant to inference, and it takes additional time to retrieve the relevant information. To test whether visual relations do indeed elicit visual images, we carried out a brain-imaging experiment (Knauff, Fangmeier, and Ruff, 2002;. Knauff, Fangmeier, Ruff, and Johnson-Laird, 2002).

Experiment 3 examined the four sorts of relations. The participants were 12 healthy male right-handed volunteers. The reasoning problems were identical to the transitive inferences used in Experiment 2. The participants' task was to decide whether or not a given conclusion followed from the premises. They made their response by pressing the appropriate key. The problems were presented verbally via pneumatic headphones, eliminating the need for visual input. There were eight problems for each of the four sorts of relations, yielding a total of 32 problems. The 32 problems were presented in four separate runs, each contained four blocks with one problem pair for each of the problem types (visuo-spatial, visual, spatial, and control). The problem pairs were randomly determined for each problem type and they remained constant throughout the experiment for all participants. The problems were randomly assigned to the runs of each subject. The order of the problem within one run was also randomly determined. Half of the problems were valid, the other half invalid. The inference tasks were identical in all respects, except for the nature of the relations. A rest interval of similar length was included between problems which differed only in lack of problem presentation. The details can be found in Knauff, Fangmeier, Ruff, and Johnson-Laird (2002).

The response latencies showed a similar pattern to those of Experiment 2; correct responses were slower for the visual problems (2.1 s) than for the control inferences (2.0 s), visuo-spatial (2.0 s), and spatial inferences (2.0 s). The differences were not reliable, however, probably because of the small sample size (Friedman analysis of variance $F = 4.64$; $p = 0.20$).

Although the control problems were the baseline condition for assessing differences in the neural processing of the different sorts of relations, the additional rest condition was initially used to determine the activation evoked by the entire set of reasoning problems. Hence, the analysis of the imaging data was carried out in two steps. The first analysis was performed to identify the cortical areas active for reasoning in general (visual, visuo-spatial, spatial, and control problems vs. the rest condition). The second analysis was carried out to examine differences among the four sorts of relation. We expected that reasoning in general should evoke activity in the spatial (dorsal) pathway, in particular in BA 7. But, if the participants generated visual images for the visual relations, then only these relations should activate areas of the brain devoted to the processing of visual information.

The results corroborated our predictions. Reasoning in general led to bilateral activity in parietal cortices. The first analysis showed that activation was similar for the four sorts of relation in comparison with the rest period. The active parietal areas in this contrast are presented in Figure 3. The figure shows that all four sorts of reasoning led to bilateral activity in the precuneus (BA 7), and in right superior parietal cortex (BA 40).

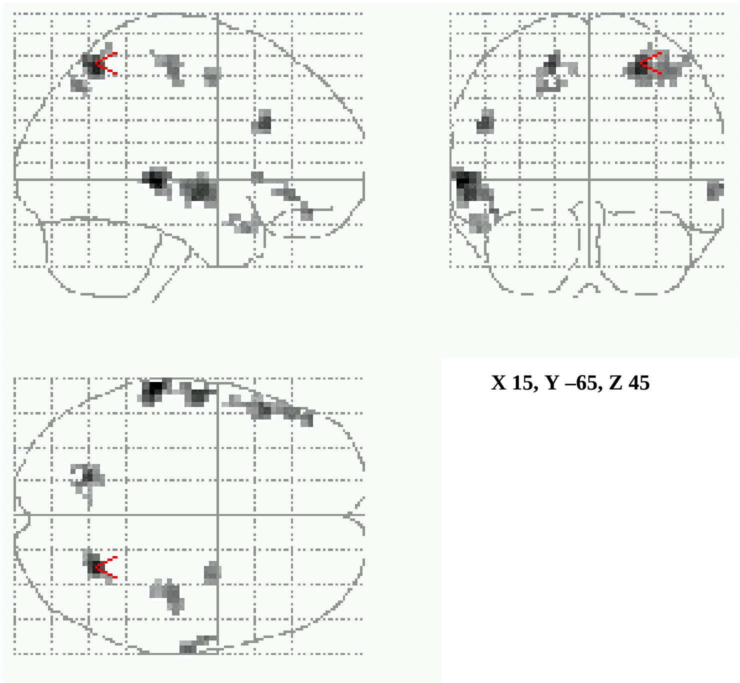

Fig. 3. All four sorts of reasoning activated the bilateral parietal cortex. The figure shows the contrast in activation between the four sorts of reasoning problem and the rest condition. In the pictures, all activities were transferred to an arbitrary gray scale, and projected onto saggital, coronal, and transverse sections of a standard brain template. Slice positions according to the Talairach atlas are given in the lower right corner of the figure (X, Y, Z, coordinates). Crosshairs are positioned in the local peak voxel for the respective contrast and brain area.

The second analysis compared reasoning with the control relations with each of the other sorts of relation: visuo-spatial, visual, and spatial. It showed that only the visual relations led to additional activation in an area that covers parts of the visual association cortex (corresponding to BA 18) and the precuneus (BA 31). These additional areas are shown in Figure 4.

Experiment 3 and previous studies (Goal and Dolan, 2001; Knauff, Mulack, Kassubek, Salih, and Greenlee, 2002) yield a consistent pattern of results: a neural correlate of deductive reasoning is located in a bilateral occipito-parietal-frontal network distributed over parts of the prefrontal cortex and the cingulate gyrus, the superior parietal cortex, and the precuneus. The parietal cortex is considered to be an area that

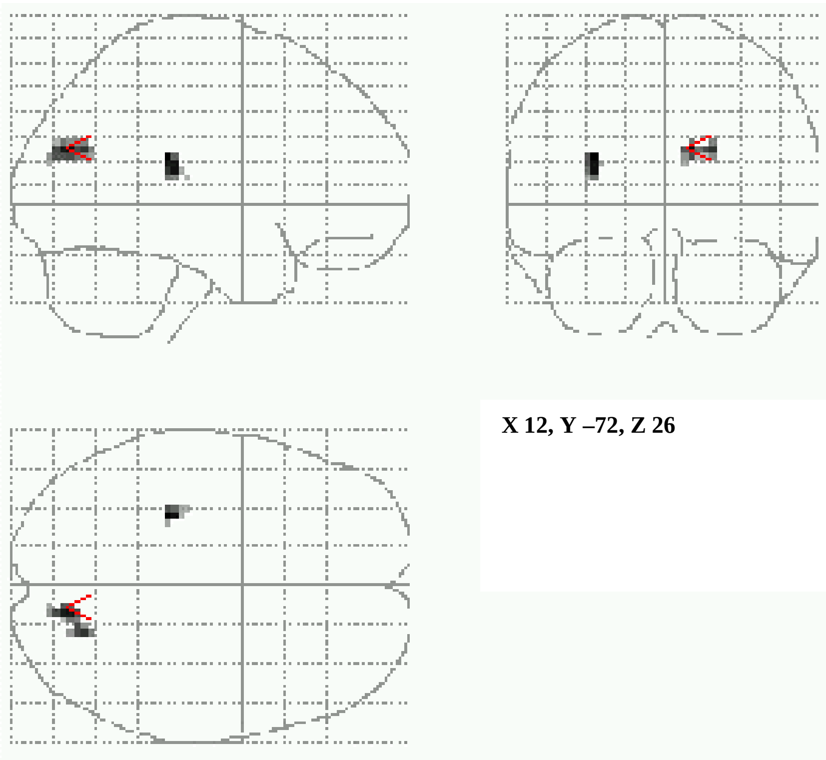

Fig. 4. Cortical regions significantly activated by reasoning with visual relations, such as *dirtier* and *cleaner* as compared to control relations). The figure shows the activity in the occipital cortex, corresponding to secondary visual cortex (V2, BA 18). Slice positions according to the Talairach atlas are given in the lower right corner of the figure. Crosshairs are positioned in the local peak voxel for the respective contrast and brain area.

combines information from different sensory modalities to form cognitive representations of space (see, e.g., Andersen, 1997). Hence, the results suggest that deductive reasoning is based on spatial representations and processes. In addition, the visual relations activated regions in visual association cortex (V2). This result corroborates the *visual-impedance* hypothesis. Visual details impede reasoning because they are irrelevant to the process. The hypothesis is accordingly borne out by the additional activity in visual areas of the brain. This activity occurred only with the visual relations, and the activated areas were not in primary visual cortex, but in visual association areas. Thus, the strongest hypothesis that imagery evokes activity in primary visual cortex (e.g Kosslyn, 1994) was not supported by the present data. But, several other imaging studies have shown that mental imagery does not necessarily active the primary visual cortex, but higher visual areas (e.g. Knauff, Kassubek, Mulack, and Greenlee, 2000).

4 Conclusions

The starting point of our experiments was the assumption that the conflicting results in the literature on mental imagery and deductive reasoning arose from a failure to distinguish between visual and spatial modes of representation. We accordingly proposed a *visual-impedance* hypothesis: relations that elicit visual images without a component relevant to inference impede reasoning. The behavioral experiments supported this hypothesis. Moreover, the impedance effect resolves some of apparent inconsistencies in the literature. Those studies that found a facilitating effect of imagery tended to use materials that differed in the ease of constructing spatial representations, whereas those studies that found no such effect, or an impeding effect of imageability, tended to use materials that evoked visual representations (see Knauff and Johnson-Laird, in press).

The brain imaging experiment provided further evidence that visual impedance is a result of the spontaneous tendency to construct visual images when the material is easy to visualize. These visual images are usually irrelevant for reasoning. Our reasoning problems were so easy that such irrelevant visual images were unlikely to lead individuals into error; but they did slow down the process. The inferential system has to find the pertinent information amongst the details and may have to suppress the irrelevant visual detail. One corollary is that visual imagery is *not* a mere *epiphenomenon* playing no causal role in reasoning (e.g. Pylyshyn, 1981). It can even be a nuisance in thinking.

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