Visual Imagery in Deductive Reasoning: Results from experiments with sighted, blindfolded, and congenitally totally blind persons

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Abstract

We report three experiments on visual mental imagery in deductive reasoning. Reasoning performance of sighted participants was impeded if the materials were easy to envisage as visual mental images. Congenitally totally blind participants did not show this visual-impedance effect. Blindfolded participants with normal vision showed the same pattern of performance as the sighted. We conclude that irrelevant visual detail can be a nuisance in reasoning and impedes the process.

Introduction

Various sorts of evidence are compatible with the conjecture that visual mental imagery is a vital part of human cognition, including the famous studies of the mental rotation and the mental scanning of images (Shepard & Cooper, 1982; Kosslyn, 1980). The aim of the present paper, however, is to show that visual mental imagery is *not* necessary in reasoning. It can even be a nuisance in reasoning and impedes the process. The article is motivated by the distinction between visual and spatial representations and processes that has been introduced by Ungerleider and Mishkin (1982). In addition, the article is motivated by studies showing that congenitally totally blind persons are as good as sighted in the construction and application of spatial representations (e.g. Kerr, 1983), but differ from sighted people in their use visual images.

The paper begins with a brief summary of previous findings on imagery and reasoning. We focus on deductive reasoning, in which the truth of the premises ensures the truth of the conclusion. We then outline our hypothesis regarding the connection between visual images, spatial representations, and congenital blindness. We report three experiments that test this hypothesis. Finally, we draw some general conclusions about visual imagery, spatial representations, and reasoning.

An influential study of imagery and deductive reasoning was carried out by DeSoto, London, and Handel (1965), who investigated so-called three-term series problems, such as "Ann is taller than Beth.", "Cath is shorter than Beth", "Who is tallest?" and argued that reasoners represent the three individuals in a visual image, and then "read off" the answer by inspecting the image. There are several other authors who argued in the same vein (e.g. Huttenlocher, 1968; Shaver, Pierson, & Lang, 1976; Clement & Falmagne, 1986). Other authors did not find evidence that imagery plays a role in reasoning (e.g. Sternberg, 1980, Richardson, 1987; Johnson-Laird, Byrne, & Tabossi; 1989; Newstead, Pollard, & Griggs, 1986). In Knauff and Johnson-Laird (2000; 2002) we argued that a possible resolution of the inconsistency in the previous results is that these studies have overlooked the distinction between visual images and spatial representations (e.g. Ungerleider & Mishkin, 1982; Logie, 1995; Smith et al., 1995). We conducted a series of experiments to test this hypothesis. We initially accomplished rating studies to identify a set of verbal relations that varied in the ease of constructing visual images and spatial representations from it. Their results yielded three sorts of verbal relations:

1. *visuospatial relations* that are easy to envisage visually and spatially; e.g. above – below;
2. *visual relations* that are easy to envisage visually but hard to envisage spatially, e.g. cleaner – dirtier;
3. *control relations* that are hard to envisage both visually and spatially, e.g. smarter – dumber

From the three sorts of verbal relations we constructed a set of three-term- and four-term-series problems. In three experiments, visual relations such as *cleaner* and *dirtier* significantly impeded the process of reasoning in comparison with control relations such as *smarter* and *dumber*. In contrast, visuospatial relations, such as *front* and *back*, which are easy to envisage visually and spatially, speeded up the process of reasoning in comparison with control relations (Knauff & Johnson-Laird, 2002). In a subsequent neuroimaging study (fMRI) we showed that in the absence of any correlated visual input, all types of reasoning problems evoke activity in spatial areas of the brain (right superior parietal cortex, and bilaterally in the precuneus), but that only the problems based on visual relations also activated early visual areas corresponding to V2 (Knauff, Fangmeier, Ruff, & Johnson-Laird, 2003). We explained the findings by an interplay of visual images and spatial representations. For example, given the premises:

The cat is above the ape.
The dog is below the ape.

the participants construct a spatial array representing the relative positions of the three individuals:

cat
ape
dog

They evaluate a possible conclusion by checking whether it holds in the representation. Perhaps the ability to envisage spatial representations is a precursor to many forms of abstract reasoning (Johnson-Laird, 1996). Likewise, relational terms that lead naturally to spatial representations should speed up the process of reasoning. In contrast, a visual relation, such as *dirtier*, may elicit irrelevant visual detail. One imagines, say, a cat caked with mud, but such a representation is irrelevant to the transitive inference. It takes additional time to replace this vivid image with one in which dirtiness is represented in degrees. In other words, the visual relations, which are hard to envisage spatially, lead to a mental picture, but the vivid details in this picture impede the process of thinking.

If visual relations impede reasoning in sighted people, what happens if congenitally totally blind people reason with the same materials? In the last two decades, comparisons between blind and sighted people have been made on a large variety of visuospatial tasks, involving mental scanning, mental rotation, memory for paths and words, etc. (e.g. Kerr, 1983; Marmor & Zaback, 1976; Zimler & Keenan, 1983). They always reported the same results: people who are blind from birth are able to envisage abstract spatial arrangements, but unable to envisage visual mental images. Most of the explanations rely on the distinction of two different neural pathways associated with the processing of "what" and "where" information (Ungerleider & Mishkin, 1982). The distinction is well-established in numerous fields of cognitive science (e.g. Kosslyn, 1994; Landau & Jackendoff, 1993), and is supported by investigations with brain damaged patients (e.g., Newcombe, Ratcliff, & Damasio, 1987), neuroimaging studies (e.g., Smith et al., 1995), and experiments on visual and spatial working memory (c.f. Logie, 1995).

The "what" and "where" distinction in mental imagery has also been studied with congenitally blind participants. Vecchi (1998) conducted experiments in the dual-task paradigm with participants who were blind from birth and report that mental imagery can rely on purely spatial representations without a visual component. In a PET study, Büchel, Price, Frackoviak, and Friston (1998) demonstrated that congenitally blind people show task-specific activation in parietal association areas, whereas blind participants who lost their sight after puberty show additional activation in the primary visual cortex in the same task (Braille reading). Luzzatti et al. (1998) in a case study showed that visual and spatial imagery can be differentially impaired after brain injuries. All these studies clearly show that visual and spatial imagery are functionally independent processes which must rely on different neural systems.

What does that mean for the hypothesis that the ability to envisage spatial representations is a precursor to reasoning, but visual imagery can impede the process? The results concerning visual and spatial imagery in the congenitally blind motivate the following hypothesis:

Relations that elicit visual images containing details that are irrelevant to an inference should impede the process of reasoning in sighted people. They, however, should not hinder the reasoning of congenitally totally blind people, because they are able to construct spatial representations without being sidetracked by irrelevant visual images.

The aim of the following experiments is to test this hypothesis. In Experiment 1 sighted students solved three-term-series problems with the three sorts of verbal relations, in Experiment 2 people who were blind from birth, and in Experiment 3 sighted people who were blindfolded to remove any visual input.

Experiment 1: Sighted Participants

In our previous experiments (Knauff & Johnson-Laird, 2000; 2002) the reasoning problems were presented visually as sentences on the screen. The aim of the first experiment was to replicate the visual-impedance effect with sighted people but with an auditory presentation of the materials.

Participants. We tested 24 sighted undergraduate students from the University of Oldenburg (mean age 22.7; 18 female, 5 male), who received a course credit for their participation.

Materials. The experiment used the set of verbal relations that has been identified in Knauff and Johnson-Laird (2000; 2002). The three sorts of relations were:

1. *visuospatial relations:* above – below, front – back
2. *visual relations:* cleaner – dirtier, fatter — thinner
3. *control relations:* better — worse, smarter – dumber

From these verbal relations we constructed a set of three-term series problems which all concerned the same terms (*dog*, *cat*, *ape*). Here is an example of a problem with a valid conclusion:

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

All sentences of the reasoning problems were recorded as audio files, edited for similar length and normalized for loudness and peak gain. Half of the problems had valid conclusions and half had invalid conclusions. The participants were told to evaluate whether the conclusion followed from the premises. In the example, cleaner and dirtier are used once in each premise, and cleaner occurs in the conclusion. But, in the experiment as a whole, each relation and its converse occurred equally often in each premise and in the conclusion.

Design. The participants acted as their own controls and evaluated 8 inferences of all three sorts (visuospatial, visual, and controls), making a total of 24 three-term series problems. The relations in these problems were those given above. The problems were presented in a randomized order over the set of participants.

Procedure. The participants were tested individually in a quiet room, and they sat at a PC that administered the experiment. The reasoning problems were presented in auditory format via headphones. The participants were told to evaluate whether or not the conclusion followed necessarily from the premises. They were instructed to respond as accurately and quickly as possible. They made their response by pressing the appropriate key on the keyboard, and the computer recorded their response and latency. Prior to the experiment, there were four practice trials.

Results and Discussion. Table 1 presents for all three of our experiments the percentages of correct conclusions and their mean latencies for the different sorts of relational inferences. The present inferences were relatively easy (92.5% correct overall) and there was no significant difference between accepting valid conclusions (94.5% correct) and rejecting invalid conclusions (95.2% correct). Thus, we pooled the results from these conditions.

The MANOVA for dependent measures on the accuracy data revealed a reliable difference across the three sorts of problems, $F(2, 46) = 5.30$, $p < .01$. There was also a difference in the mean number of correct responses between the visual problems and the control problems, $F(1, 23) = 6.57$, $p > .02$, and the (not orthogonal) contrast between visuospatial and visual problems was significant, $F(1, 23) = 6.57$, $p < .02$. The response latencies also showed the predicted trend (visual relations resulted in longer response latencies than control problems and reasoning with these problems in turn took longer than with visuospatial problems), but the main effect across the three sorts of problems was statistically not significant, $F(2, 46) = .53$, $p >.6$.

The main goal of the experiment was to test a new experimental setup that can be used with the blind people later on. The experiment was successful in showing that the visual-impedance-effect also appears with the auditory presentation of the materials. Thus, we can use the same experimental setting in the later studies. A second corollary from the findings is that the visual-impedance effect does not depend on the visual presentation of the materials. It rules out that the impedance is simply due to interference between the visual process of reading the premises and conclusions and the mental activity of envisaging a visual mental image to solve the problem. Instead, the findings again emphasize the importance of distinguishing between visual and spatial representations. Visual relations such as *fatter* and *thinner* impeded the process of reasoning in comparison with control relations such as *smarter* and *dumber*. In other words, the visual relations, which are hard to envisage spatially, lead to a mental picture, but the vivid details in this picture impede the process of thinking.

Experiment 2: Congenitally Totally Blind Participants

This experiment directly tests the hypothesis that the visual relations do not impede the reasoning of congenitally totally blind people, because they are able to construct spatial representations without being sidetracked by irrelevant visual images.

Participants. We tested 10 congenitally totally blind participants (mean age 24.8; 7 female, 3 male). According to the German Law, a person is congenially totally blind, if she or he has less than 5% of normal vision and got blind before the age of 2. Most of the participants were blind from birth due to retinopathy of prematurity. The participants we recruited from two self-helping groups for the blind. All participants gave their informed consent prior to the participation in the study.

Materials, Design, and Procedure. The materials and the design were identical to Experiment 1. The instructions were read to the participants by one of the experimenters. The participants were tested individually in a quiet room at the institutions, and they sat in front of a Laptop that administered the experiment. Except of the two keys associated with "yes" and "no" and the spacebar, all other keys were removed from an external keyboard.

Results and Discussion. The second row of Table 2 presents the mean latencies and correct responses to the three sorts of relational inferences. Overall, the blind responded correctly to 76.2 % of the inferences and again there was no significant difference between accepting valid conclusions (76.7% correct) and rejecting invalid conclusions (75.8% correct). Hence, we pooled the results from these conditions.

The ANOVA showed no significant difference in reasoning accuracy between the three sorts of problems, $F(2, 18) = .36$, $p > .70$, and none of the single contrast revealed a significant difference (visual vs. control: $F(1, 9) = 2.38$, $p > .63$; visuospatial vs. control: $F(1, 9) = .70$, $p > .79$; visuospatial vs. visual: $F(1, 9) = .74$, $p > .41$). In the response latencies there was also no difference between the three sorts of problems, $F(2, 18) = .928$, $p > .41$, and not one of the single contrast showed a significant difference (visual vs. control: $F(1, 9) = 1.51$, $p > .24$; visuospatial vs. control: $F(1, 9) = 1.32$, $p > .28$; visuospatial vs. visual: $F(1, 9) = .35$, $p > .56$).

The results shed new light on the role of visual images and spatial representation in reasoning. Mental representations must be derived from perception and thus the representations of persons who are blind from birth must be different to that of sighted persons. In particular, haptics or auditory perceptions lead to spatial representations without a visual component. This account is supported by several studies that report the same *pattern of performance* in highly spatial tasks in sighted and congenitally blind persons. In a classical study by Kerr (1983) congenitally totally blind and sighted showed almost the same pattern of response times depending on imagined distance, image size, etc. Kerr concluded that "picturability" does not affect the recall of "mental images" in the blind. The only difference was that sighted participants reported forming the images while the blind did not (or at least significantly slower). Marmor and Zaback (1976) explored Shepard and Metzler's mental rotation tasks and found that blind people also show longer reaction times for larger rotation angles. Zimler and Keenan (1983) found similar results in congenitally blind children and adults. In addition, they reported that the haptic images of the blind maintain the same *spatial* information just as the visual images of the sighted do. Obviously, people who are blind from birth do not tend to construct visual mental images. But they are able to construct and to employ spatial representations. In fact, most of our blind participants reported not using visual images. Instead, they reported that they located the objects of the inference on a spatial scale or in degrees, representing, say "dirtiness". Although such introspections certainly can be wrong, they agree with the experimental findings: The blind are able to construct spatial representations without being irritated by irrelevant visual images.

Experiment 3: Blindfolded Participants

Is there an alternative explanation for the different patterns of results in sighted and blind participants? One possible account is that the visual-impedance effect in the sighted is simply due to interference between the visual input from the surrounding and the mental activity of envisaging a visual mental image. To rule out this explanation in the third experiment the participants had normal vision, but were blindfolded to eliminate any visual input. If the visual-impedance-effect is due to interference between visual imagery and visual perception, they should be also resistant to the impedance effect of visual relations—much as the congenitally blind people are. If, in contrast, the tendency of sighted people to construct visual images is responsible for the visual-impedance effect, then the pattern of results should be similar to that in Experiment 1.

Participants. We tested 30 sighted undergraduate students of University of Oldenburg (mean age 23.3; 18 female, 10 male). They were completely blindfolded to remove any visual input. They received a course credit for their participation.

Materials, Design, and Procedure. The design, the materials and the procedure were identical to Experiment 1 and 2. As in Experiment 2, the instructions were read to the participants by one of the experimenters and except for the two keys associated with "yes" and "no" and the spacebar, all other keys were removed from an external keyboard.

Results and Discussion. Overall, there were 90.8% correct responses and there was no significant difference between accepting valid conclusions (90.2% correct) and rejecting invalid conclusions (91.6% correct). They were pooled again. The MANOVA showed a reliable difference in accuracy across the three sorts of problems, $F(2, 58) = 3.71$, $p < .03$. There was also a significant difference in the mean number of correct responses between the visual problems and the control problems, $F(1, 29) = 5.80$, $p < .03$ and the visual problems and the visuospatial problems, $F(1, 29) = 4.29$ $p < .05$

The response latencies showed that visual problems were slower than control problems, which in turn were slower than the visuospatial problems. The main effect across the three types of problems is statistically significant, $F(2, 58) = 4.22$, $p < .02$. The difference between visual and control relations did not reach statistical significance, $F(1, 29) = 2.25$ $p > .14$, but the difference between visual and visuospatial problems was reliable, $F(1, 29) = 7.01$, $p < .02$.

The pattern of performance in the blindfolded participants is almost identical to that of the sighted participants in Experiment 1. There was again the trend visual > control > visuospatial (although the single contrast between visual and control problems did not reach statistical significance in the lantencies). These data clearly show that the characteristics of the reasoning problems lead to the visual-impedance effect. It is not simply due to interference between the visual input from the surrounding and the mental activity of envisaging a visual mental image.

Table 1: Percentages of correct responses and their mean response latencies (in s) in the three experiments as a function of the different sorts of relations: visual relations, control relations, visuospatial relations.

	Visual inferences	Control inferences	Visuospatial inferences
sighted (Exp 1)	86.9%	94.8%	94.8%
	1.26	1.01	.97
blind (Exp 2)	75.0%	73.6%	79.9%
	5.24	5.29	6.06
blindfolded (Exp 3)	86.7%	92.9%	92.9%
	1.42	1.08	.86

General Discussion

The starting point of our studies was the distinction between visual and spatial modes of representation in reasoning. Previous studies enabled us to identify visuospatial relations, such as *above-below*, which are easy to envisage both visually and spatially, visual relations, such as *cleaner-dirtier*, which are easy to envisage visually but hard to envisage spatially, and control relations, such as *better-worse*, which are hard to envisage both visually and spatially. Our former studies showed that visual relations significantly impede the process of reasoning by slowing it down. We refer to that as *visual-impedance-effect* (Knauff & Johnson-Laird, 2002).

In the present studies we tested a group of sighted participants, one group of congenitally totally blind participants, and one group of blindfolded participants with normal vision. In the sighted participants the visual relations significantly impeded the process of reasoning by slowing it down. The blindfolded did show the same impedance effect. But, the participants who were blind from birth were not affected by the ease of envisaging the verbal relations visually. They showed the same reasoning performance across all sorts of problems.

What might cause visual imagery to impede reasoning in the sighed participants? A theory that relies on visual imagery as the medium for reasoning is implausible, because individuals can reason about relations that they cannot visualize. Similarly, such a theory cannot readily explain why relations that are easy to envisage visually impeded reasoning. One could object that the ability to visualize the visual relations was impeded by the concurrent visual perception. In fact, several studies have shown that visual imagery and visual perception interfere and that visual imagery performance is impaired under this condition (c.f Logie, 1995). Our third experiment with the blindfolded participants, however, clearly falsifies this hypothesis. An explanation based on formal inference rules (Rips, 1994; Braine & O'Brien, 1998), is also questionable, because it does not account for the effects of content, and does not immediately suggest an explanation of the visual impedance effect.

The present findings support a spatial account of reasoning. The initial idea has been introduced by Huttenlocher (1968) and was further elaborated in the mental models theory of reasoning (Johnson-Laird, 1983; Johnson-Laird & Byrne, 1991). The model theory does not rely on linguistic processes like rule-based-approaches of reasoning (Braine & O'Brein, 1998; Rips, 1994). Such processes are relevant only to transfer the information from the premises into a spatial array and back again, but the reasoning process itself totally relies on non-linguistic processes for the construction and inspection of spatial mental models. The mental models mirror the spatial relations between the represented objects. In contrast to visual images, mental models can represent any possible situation and can abstract away from such visual details as colors, textures, and shapes (Johnson-Laird, 1983; Johnson-Laird & Byrne, 1991). Mental models can also represent class-inclusion, temporal order, and abstract relations such as ownership (c.f. Johnson-Laird & Byrne, 1991). Several studies have shown that the content can facilitate inferences in certain cases and impede them in other cases (e.g. Johnson-Laird & Byrne, 2001). Likewise, a visual relation, such as *dirtier than*, can elicit a vivid visual detail, such as an animal caked with mud that is irrelevant to an inference. It will then take additional time to retrieve the information needed to construct the appropriate spatial mental model for making the inference.

The blind participants, however, did not show this visual impedance effect. This provides additional support for the spatial account of reasoning. Clearly, people who are blind from birth do not tend to use visual mental images, unless they are forced to do so, as in the studies from the literature. But they are able to construct and to employ spatial representations. Such models represent the objects of the inference in degree or on a spatial scale. For this reason, they are not sidetracked by irrelevant visual images and thus perform *relatively* better than sighted persons in the visual problems.

There are, however, some ambiguities in the data from the blind. First, the data are in line with other studies that compared blind and sighted people on a large variety of visuospatial tasks. They consistently reported that blind persons in *absolute* terms perform less accurately or more slowly than the sighted on such tasks (e.g. Kerr, 1983). Such an overall deficit of the blind participants is also visible in the present studies. The sighted participants solved on average 92.2% of the inferences correctly, but the blind participants only 76.2%. The sighted needed 1.08 seconds on average to respond to a problem; the participants who were blind from birth needed 5.3 seconds. Even the blindfolded participants from Experiment 3 performed much better than the blind persons. The dominant approach to explain such findings runs somewhat counter to our own account. It is usually seen as a *visual imagery deficit* of the congenitally blind. In particular, haptics or auditory perceptions also lead to spatial representations, but it is argued that these representations might be sub-optimal compared to vision-based representations (a recent discussion can be found in Fleming, Ball, Collins, & Ormerod, in press). From this view, our blind participants show less good performance, because they are less good in visual mental imagery. However, this account cannot readily explain why the impedance effect of visual relations disappears in the blind. If a visual imagery deficit is responsible for the overall performance deficit of the blind, the impedance effect should be even more pronounced in the blind compared to the sighted.

A second critical aspect in the data is that 9 out of 10 blind participants showed a minor increase of response latencies in the visual problems. The differences were particularly small and apparent only in the visual inspection of the data. However, one could argue that under these conditions the non-effect in the MANOVA (and in the post-hoc computed nonparametric tests) is just due to the small number of participants. If the effect would turn out to be reliable it could have two causes: It could either indicate that even the blind try to envisage the visual relations in a visual mental image (what is implausible due to the above reasons) or that the relations differ in the degree to which they imply transitivity. Spatial relations are unequivocal, but visual relations might be more dubious. Given, say, the following premises:

The cat is fatter than the ape.

The ape is fatter than the dog.

Reasoners might have wondered whether the fatness of cats, apes, and dogs, is commensurable. They claim that, say, an elephant is thin is relative to elephants, and so it is sensible to assert that a thin elephant is fatter than a fat dog. The criterion for fatness shifts from one animal to another. This factor might have confused reasoners in our experiment, and impeded their inferences with the visual relations. A related factor is the degree to which the premises accord with the participants' existing beliefs. For example, the preceding premise (The cat is fatter than the ape) might strike some individuals as implausible. However, these explanations are unlikely, because in the experiments as a whole, each such plausible premise is matched with one using the converse relation (The cat is thinner the ape), and so this factor seems not likely to account for our results.

A last point is that we did not use purely spatial relations, i.e., those that are hard to envisage visually but easy to envisage spatially. If, as our findings suggest, the visual character of the materials leads to an impairment of reasoning performance, whereas the possibility of spatially envisaging the materials speeds up reasoning, then tasks based on purely spatial relations should be processed most quickly. Indeed, we found a (not significant) trend in this direction in Knauff & Johnson-Laird (2002). However, we encountered some technical problems with these relations and some colleagues overall doubt the existence of such relations.

In conclusion, our results suggest that the content of verbal relations can affect the process of inference. If the content yields information relevant to an inference, as it does with visuospatial relations, then reasoning proceed smoothly, and may even be slightly faster than with other sorts of content. But, if the content yields visual images that are irrelevant to an inference, as it does with visual relations, then reasoning of sighted persons is impeded and takes reliably longer. People who are blind from birth are *immune* to such impedance effects, since they do not tend to use disrupting visual images. A word of caution, on the other hand, is that the visual and spatial nature of representations in reasoning also depends on the nature of the problem. Transitive inferences might elicit spatial representations, but that does not rule out that other problems rely on visual images in addition.

Acknowledgments

M.K. is supported by a Heisenberg Award from the Deutsche Forschungsgemeinschaft (DFG) and by the grants Kn465/2-4 and BACKSPACE in the Transregional Collaborative Research Center on Spatial Cognition (SFB/TR 8). The authors are grateful to Jack Loomis, who had the initial idea of testing the visual-impedance-hypothesis with blind people. We are also indebted to three anonymous reviewers and to Mrs. Backsmann and Mr. Becker from the self-helping groups in Oldenburg and Hannover.

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