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Mental imagery, reasoning, and blindness

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Although reasoning seems to be inextricably linked to seeing in the "mind's eye", the evidence is equivocal. In three experiments, sighted, blindfolded sighted, and congenitally totally blind persons solved deductive inferences based on three sorts of relation: (a) visuo-spatial relations that are easy to envisage either visually or spatially, (b) visual relations that are easy to envisage visually but hard to envisage spatially, and (c) control relations that are hard to envisage both visually and spatially. In absolute terms, congenitally totally blind persons performed less accurately and more slowly than the sighted on all such tasks. In relative terms, however, the visual relations in comparison with control relations impeded the reasoning of sighted and blindfolded participants, whereas congenitally totally blind participants performed the same with the different sorts of relation. We conclude that mental images containing visual details that are irrelevant to an inference can even impede the process of reasoning. Persons who are blind from birth—and who thus do not tend to construct visual mental images—are immune to this visual-impedance effect.

One of the most fundamental and frequently asked questions within cognitive psychology is: "What type of mental representation is used when people think, solve problems, or make decisions?" If you ask people with no education in psychology how they reason, many of them say that they rely on visual mental images. For instance, with a problem such as:

Adam is taller than Brenda.

Brenda is taller than Cathy.

Does it follow that Adam is taller than Cathy?

they say that they form a mental picture in their "mind's eye" and then look at this picture to see that Adam is taller than Cathy (Knauff, Strube, Jola, Rauh, & Schlieder, 2004). Not only nonpsychologists, but also many cognitive psychologists have claimed that reasoning is inextricably linked

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to seeing in the "mind's eye" (e.g., DeSoto, London, & Handel, 1965; Kosslyn, 1994). The aim of the present paper is to explore the issue of mental representation in reasoning with a special focus on visual mental images. We reexamine the hypothesis that visual representations underlie reasoning, reject it, and propose an alternative view. We show that previous reasoning studies have often overlooked a possible confounding between materials that invoke *visual* imagery and materials that invoke *spatial* representations. In addition, the article is concerned with the connection between reasoning and blindness. On the one hand, the visual nature of reasoning might suggest that congenitally totally blind individuals—who do not experience visual mental images—should be impaired in reasoning with highly visual materials (e.g., Fraiberg, 1980). On the other hand, there are several studies showing that persons who are blind from birth differ from sighted people in their use of visual images, but that they are as good as the sighted in the construction of spatial representations (e.g., Kerr, 1983). 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 explain why we believe that previous reasoning studies have often overseen a possible confounding between visual imagery and spatial representations. Based on these thoughts, we outline our hypothesis that reasoning relies on spatial representations, whereas visual mental imagery is not necessary in reasoning. We report three experiments with sighted, congenitally totally blind, and blindfolded sighted participants that test this hypothesis. Finally, we draw some general conclusions about visual imagery, spatial representations, and reasoning.

A first study on imagery and deductive reasoning was carried out by DeSoto et al. (1965). They investigated three-term series problems as in the preceding example and argued that reasoners represent the three individuals in a visual image and then "read off" the answer by inspecting the image "in the minds eye". Huttenlocher (1968) also claimed that reasoners construct a visual mental image of the individuals in the problem that is analogous to seeing the individuals. Shaver, Pierson, and Lang (1975) claimed that performance on three-term series problems depends on the ease of creating an image of the given materials, the instruction to form images, and the participants' ability to form images. Clement and Falmagne (1986) found that materials rated as easy to imagine led to fewer errors in reasoning. Pearson, Logie, and Gilhooly (1999) reported that a visual secondary task has a disrupting effect on reasoning-related mental synthesis.

Other authors questioned the role of visual imagery in reasoning. Johnson-Laird, Byrne, and Tabossi (1989) examined reasoning with three transitive relations: *equal in height, in the same place as*, and *related to* (in the sense of kinship) and found no effect of imageability on reasoning accuracy. Clement and Falmagne (1986 studied conditional reasoning tasks such as *If a man walks his golden retriever, then he gets upset about his insect bite*, which were assumed to be highly visual, and problems based on statements such as *If the man takes an economic perspective, then he uses the new memory technique*, which were assumed to be difficult to visualize. A second factor was the availability of pertinent knowledge. This factor interacted with imageability, but in the direct comparison there was no difference between problems based on statements that were easy to imagine visually and those that were difficult to visualize. Newstead, Pollard, and Griggs (1986) reported a similar result, and Sternberg (1980) found no difference in the accuracy of solving problems that were easy or hard to visualize and no reliable correlation between scores on the imageability items of IQ tests and reasoning ability. Richardson (1987) reported that reasoning with visually concrete problems was no better than reasoning with abstract problems.

One possible resolution of the inconsistencies in the previous findings is that these studies have overlooked the distinction between visual and spatial representations. This distinction has been drawn by many researchers in cognitive psychology (e.g., Johnson-Laird, 1998; Klauer & Zhao, 2004; Logie, 1995), cognitive neuroscience (Kosslyn, 1994; Rueckl, Cave, & Kosslyn, 1989; Ungerleider & Mishkin, 1982), and psycholinguists (e.g., Landau & Jackendoff, 1993). The distinction is often referred to as the *what* versus *where* distinction and is especially important in the theory of working memory. In the classical model by Baddeley and Hitch (1974), visual and spatial information was maintained and processed in one uniform system—the *visuo-spatial sketch pad.* Recent studies, however, have shown that this part of working memory consists of two specialized temporary memory systems—one visual and one spatial. The visual component is responsible for retaining visual features such as shape, texture, colour, and metrical distance. The spatial component holds locations and movement information—that is, it represents what things are where. Studies using the dual-task interference paradigm showed that the maintenance of visual information such as shape or colour interferes with a visual perceptual input (Logie, 1986; Logie & Marchetti, 1991; McConnell & Quinn, 2000; Quinn & McConnell, 1996, 1999). In contrast, the retention of spatial information interferes with movements generated in response to targets (Baddeley & Lieberman, 1980; Logie & Marchetti, 1991; Smyth & Scholey, 1994). In addition, by using the dual-task paradigm Klauer and Zhao (2004) showed a direct double dissociation. In their studies, a visual short-term memory task was more strongly disrupted by visual than spatial interference, and a spatial memory task was simultaneously more strongly disrupted by spatial than visual interference (Klauer & Zhao, 2004).

Brain imaging studies also provide strong evidence for a dissociation of the two systems and that different cortical areas contribute in different ways to the processing of visual and spatial information. These studies fall into two groups. The first group was primarily concerned with the responsibility of the prefrontal cortices (e.g., Courtney, Ungerleider, Keil, & Haxby, 1996; Goldman-Rakic, 1987; Haxby, Ungerleider, Horwitz, Rapoport, & Grady, 1995; Mecklinger, Bosch, Grünewald, Bentin, & von Cramon, 2000; Owen, Evans, & Petrides, 1996; Smith & Jonides, 1999). The second group of studies investigated the role of the ventral and dorsal pathways for visual and spatial working memory. The main motivation of these studies was to explore whether the brain areas that are specialized for the perception of objects, features, and locations are also involved if such information has to be maintained in working memory. Therefore, in a study by Smith et al. (1995), participants had to perform either spatial memory tasks (remembering positions of objects) or visual memory tasks (remembering the identity of objects). The results manifested a double dissociation, since the spatial tasks activated occipital and parietal (right-hemispherical) regions—that is, regions of the dorsal "where" pathway—while the visual tasks resulted in activation in (left-hemispherical) inferotemporal regions—that is, areas of the ventral "what" pathway. These results were replicated in a study by Courtney et al. (1996), who found activation in the ventromedial temporal lobes—that is, parts of the "what" pathway—when participants had to maintain faces in working memory, while the superior and inferior parietal cortex—that is, parts of the "where" pathway—were activated when spatial locations were maintained in working memory. Similar findings have been reported in other studies (e.g., Postle & D'Esposito; 2000; Smith & Jonides, 1997, and in an overview article by D'Esposito et al., 1998). All together, the results of the brain imaging studies are in good agreement with the findings from behavioural experiments and establish the distinction of visual and spatial representations: Visual working memory tasks interfere with other visual tasks but not with spatial tasks, whereas spatial tasks are disrupted by other spatial tasks but not by visual. Visual memory tasks are related to activity in the inferior temporal cortex, whereas spatial memory tasks activate the dorsal pathway, namely visual association areas and areas in the parietal cortex. Based on these findings visual representations are often thought to be visual mental images. They are seen as structurally similar to real visual perceptions. They have a limited resolution, but individuals can scan and mentally manipulate them (see, e.g., Finke, 1989; Kosslyn, 1980). Visual mental images can be so similar to real perceptions that they can be confused for them: The now classical Perky effect (Perky, 1910; see also: Johnson & Raye, 1981).[1] In contrast, spatial representations are models of the spatial relations among entities. Individuals might also use them to represent abstract relations in a spatial way—for example, class inclusion can be represented by the spatial inclusion of one area within another. In inferential tasks, spatial representations are likely to exclude visual detail, to represent only the information relevant to inference, and to take the form of multidimensional arrays that maintain ordinal and topological properties. In sum, visual images represent information in a modality-specific format, whereas a spatial representation is abstract and not restricted to a specific modality.[2]

What does the distinction between visual images and spatial representations mean for reasoning? Knauff and Johnson-Laird (2002) investigated the role of spatial representations in reasoning and related their findings to the theory of mental models (Johnson-Laird, 1983; Johnson-Laird & Byrne, 1991). According to this view, mental models are not to be identified with visual images (Knauff & Schlieder, 2005). On the one hand, a relation such as *The man is behind the woman* is easy to envisage as a visual mental image. It may, however, also be represented as a spatially organized mental model without any conscious awareness of a visual image. Such a spatial model, according to the theory of mental models, suffices for reasoning, because it represents the relevant logical properties. Given premises of the form:

A is above B.

B is above C.

reasoners can build a mental model that satisfies the premises:

A

B

C

From this model the conclusion *A is above C* follows. A relation such as *The dog is dirtier than the cat*, in contrast, is easy to visualize, but it seems much less likely to be represented spatially. In this case, reasoners might tend to form a visual image of a dirty dog and an image of a less dirty cat. However, Knauff and Johnson-Laird (2002) argued that such an image contains a large amount of visual detail that is irrelevant to the inference. Accordingly, reasoners have to isolate the information that is relevant to the inference, and in so doing they might be side-tracked by irrelevant visual details. Hence, it is likely that a visual image can even impede the process of reasoning. Knauff and Johnson-Laird (2002) found initial evidence in support of this account. 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 the present paper, we use a new experimental paradigm to investigate the role of visual mental imagery in reasoning: What happens if congenitally totally blind participants reason with materials in which the ease of visualization is systematically varied? Many, if not all, of our mental representations are correlated with our experiences and perceptions, and thus the representations of persons who are blind from birth are different from those of sighted persons. In particular, a relation such as *The cat is dirtier than the dog* is unlikely to be visualized by persons who are blind from birth, but might be envisaged visually by the sighted. Other relations such as *The dog is behind the cat* might also be visualized by the sighted, but may also be readily represented

[1] The "Perky effect" is named after Cheves Perky who discovered it in 1910. The principle is that mental imagery supports visual perception and that people often merge images and what is actually seen.

[2] Some authors (e.g., Farah, Hammond, Levine, & Calvanio, 1988; Levine, Warach, & Farah, 1985) refer to the use of spatial representations as "spatial imagery", and we did that in earlier publications too (Knauff, Mulack, Kassubek, Salih, & Greenlee, 2002). In the present paper, however, we prefer to use the term "spatial representations" to avoid any terminological confusion.

spatially. One corollary from the visual imagery account of reasoning might be that individuals who are blind from birth should be worse at reasoning with visual materials. However, the results on visual and spatial representations in the blind, together with our previous studies, motivate an alternative hypothesis: Relations that elicit visual images containing details that are irrelevant to an inference should impede the process of reasoning in sighted people. They should not, however, 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. We start with a brief summary of a pilot study reported in Knauff and Johnson-Laird (2002). Then we report three experiments on reasoning with transitive relations. In Experiment 1 sighted individuals solved three-term series problems with different sorts of relation. In Experiment 2 people who were blind from birth solved the problems, and Experiment 3 was carried out with sighted people who were blindfolded to remove any visual input.

Pilot study

In Knauff and Johnson-Laird (2002) we carried out a study to determine whether the ease of visualizing a relation might be independent of the ease of forming a spatial representation of the relation. Because the obtained relations provide the basis of the present article, we briefly summarize the gist of this study here. In the study, we selected 15 pairs of relational terms (a relation and its converse) that might be instances of the different sorts of relation, including such pairs as: *cleaner–dirtier*, *uglier–prettier*, *heavier–lighter*, and *smarter–dumber*. We formed 30 assertions using these relations, such as *The cat is above the dog* and *The cat is smarter than the dog*. A total of 10 student volunteers at Princeton University, who had normal (or corrected-to-normal) vision used two separate scales to rate the ease of forming visual images and the ease of forming spatial representations from each of the assertions. The two scales had seven points, ranging from very easy to very difficult. The ratings showed that the relations do differ in the rated ease of forming both images and spatial representations of them, although we did not find any relations that were easy to envisage spatially that were not also easy to visualize. Based on the ratings, we were able to select three sorts of relation:

1. Relations such as above–below that were easy to envisage visually and spatially, which we henceforth refer to as *visuo-spatial relations.*
2. Relations such as cleaner–dirtier that were easy to envisage visually but difficult to envisage spatially, which we henceforth refer to as *visual relations.*
3. Relations such as better–worse that were difficult to envisage both visually and spatially, which we henceforth refer to as *control relations.*

The differences between the three sorts of pairs in Table 1 were statistically reliable, whereas there were no significant differences between the pairs of relations within the three sorts. Details concerning the study can be found in Knauff and Johnson-Laird (2002).

Table 1. *Results from the norming study by Knauff and Johnson-Laird (2002): Mean ratings for ease of forming a visual image and a spatial array of the three sorts of relational term*

		Ratings	
Relational terms		*Visual*	*Spatial*
Visual	cleaner–dirtier	5.1	1.6
	fatter–thinner	4.8	2.0
Control	better-worse	2.1	1.1
	smarter-dumber	2.8	1.2
Visuo-spatial	above-below	5.3	5.4
	front-back	5.2	5.3

Note: The scales ranged from 1 (very difficult) to 7 (very easy).

EXPERIMENT 1: SIGHTED PARTICIPANTS

In Experiment 1, we examined the three sorts of relational term (visuo-spatial, visual, and control) in relational reasoning with sighted participants. If our assumptions concerning the role of visual and spatial representations in reasoning are correct, then the visual relations should slow down the process of reasoning, in comparison with the visuo-spatial and control relations. However; if the imagery hypothesis is correct, reasoning relies on images, so the participants should perform better with visual relations. To avoid a confounding of visual imageability and the visual presentation of the reasoning materials (sentences on the screen), the problems were presented auditorily via headphones. This also had the advantage that the identical experimental set-up could be used with the blind participants later on.

Methods

Participants
We tested 24 sighted undergraduate students from the University of Oldenburg (mean age 22.7 years; 18 female, 6 male), who received a course credit for their participation.

Materials
The experiment used the set of verbal relations presented in Table 1. The three sorts of relation were:

1. *Visuo-spatial 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,* and *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 presented in German, 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. 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 eight inferences of all three sorts (visuo-spatial, visual, and control), making a total of 24 three-term series problems. The problems were presented in a random order across 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 computer presented the reasoning problems in auditory format via headphones. The participants were told to evaluate whether the conclusion necessarily follows 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

The four practice trails were eliminated from the analysis. All other data were analysed in analyses of variance (ANOVAs) for dependent measures. Response times were used from correct responses only. If there were two standard deviations either above or below the mean, they were replaced by the cut-off of the condition (cf. Ratcliff, 1993).

For all statistical analyses, an alpha level of 0.05 was adopted, and the proportion of the effect plus error variance that is attributable to the effect, η_p^2, was used as a measure for effect size.

Table 2 presents the proportions of correct conclusions and their mean latencies for the different sorts of relational inference (for all three of our experiments). The present inferences were relatively easy (91% correct overall), and there was no significant difference between accepting valid conclusions (90.3% correct) and rejecting invalid conclusions (91.7% correct). Thus, we pooled the results from these conditions. The analysis of accuracy data revealed that participants made about 10% more errors in the problems with visual relations than in the control problems and more than 12% more than in the visuo-spatial problems. The ANOVA on the accuracy data revealed a reliable difference across the three sorts of relation, $F(2, 46) = 10.72$, $p < .002$, $\eta_p^2 = .32$. Pairwise comparisons of the conditions also revealed differences in the mean number of correct responses between the visual relations and the control relations, $F(1, 23) = 8.85$, $p < .01$, $\eta_p^2 = .29$, and the (not orthogonal) contrast between visuo-spatial and visual relations, $F(1, 23) = 16.24$, $p < .002$, $\eta_p^2 = .41$. The response latencies also showed the predicted trend: Visual relations resulted in longer response latencies than control relations, and reasoning with these relations in turn took longer than that with visuo-spatial relations. The main effect across the three sorts of relation was close to being statistically significant, $F(2, 46) = 3.01$, $p = .059$, $\eta_p^2 = .17$, and the predicted linear trend (visual > control > visuo-spatial) was significant, $F(1, 23) = 6.51$, $p < .02$, $\eta_p^2 = .22$.

Why is reasoning with visual relations more difficult than that with the other relations? We believe that the tendency of visual relations to evoke irrelevant visual mental images is responsible for the impedance effect. The experimental findings corroborated our prediction that reasoning performance of sighted participants should be impeded by the ease of envisaging the materials visually. The visual relations resulted in more errors and longer response latencies tha did control relations. This is contrary to the visual imagery hypothesis of reasoning but in agreement with our previous findings (Knauff & Johnson-Laird, 2002). 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 the argument that the impairment 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 emphasize the importance of distinguishing between visual and spatial representations. In sighted individuals, visual relations such as *fatter* and *thinner* hinder the process of reasoning in comparison with control relations such as *smarter* and *dumber*. In other words, the visual

Table 2. *The proportions of correct responses*[a] *and their mean response latencies*[b] *in Experiments 1–3 as a function of the different sorts of relation*

	Relations											
	Visual				*Control*				*Visuo-spatial*			
	Accuracy		*Latency*		*Accuracy*		*Latency*		*Accuracy*		*Latency*	
	RF	*SD*	*M*	*SD*	*RF*	*SD*	*M*	*SD*	*RF*	*SD*	*M*	*SD*
Sighted (Exp. 1)	.84	.17	1,213	906	.94	.09	939	569	.96	.07	855	871
Blind (Exp. 2)	.80	.21	4,628	1,837	.75	.26	5,978	4,054	.73	.22	5,176	2,475
Blindfolded (Exp. 3)	.86	.14	1,421	1,240	.93	.12	1,076	732	.93	.13	864	838

[a]As relative frequency, RF. [b]In ms.

relations, which are hard to envisage spatially, lead to a mental picture, but the vivid details in this picture impede the process of thinking.

One could also argue that the relations might 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. The 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. However, this explanation, we believe, is unlikely because the effect of incommensurable premises might have affected premise processing times, but is not clear why our participants drew fewer valid inferences from the visual relations than they did from the other 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. This account, however, is also unlikely, because in the experiments as a whole, each such plausible premise is matched with one using the converse relation (the cat is thinner than the ape), and so this factor seems unlikely to account for our results.

EXPERIMENT 2: CONGENITALLY TOTALLY BLIND PARTICIPANTS

If visual relations impede reasoning in sighted people, what happens if congenitally totally blind people reason with the same materials? While most people experience space visually, congenitally totally blind individuals can only make spatial experiences with their auditory and tactile perceptions (Fraiberg, 1980). In the last two decades, researchers have made comparisons between blind and sighted people on a large variety of visuo-spatial tasks, involving mental scanning, mental rotation, memory for paths and words, and so on (Marmor & Zaback, 1976; Zimler & Keenan, 1983). They always reported the same results: People who are blind from birth are able to envisage spatial arrangements, but unable to envisage visual mental images. Most of the explanations rely on the above-mentioned distinction between the two different neural pathways associated with the processing of "what" and "where" information (Ungerleider & Mishkin, 1982). Vecchi (1998), for instance, conducted experiments in the dual-task paradigm with participants who were blind from birth and reported that mental imagery can rely on purely spatial representations without a visual component. In a PET study, Büchel, Price, Frackowiak, and Friston (1998) demonstrated that congenitally blind people show task-specific activation in spatial brain areas, whereas blind participants who lost their sight after puberty show additional activation in the primary visual cortex in the same task (Braille reading). Luzzatti, Vecchi, Agazzi, Cesa-Bianchi, and Vergan (1998) in a case study showed that visual and spatial representations and processes can be differentially impaired after brain injuries. All these studies clearly show that visual and spatial imagery are functionally independent processes that rely on different neural systems.

What does that mean for the connection between imagery, reasoning, and congenital total blindness? With the following experiment, we directly test 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. If the experiment supports this account it provides additional evidence for our more general hypothesis that visual images containing details that are irrelevant to an inference can impede the process of reasoning.

Methods

Participants

We tested 10 congenitally totally blind participants (mean age 24.8 years; 7 female, 3 male). According to German law, a person is congenitally totally blind if she or he has less than 5% of normal vision and went blind before the age of 2. Most of the participants were blind from birth due to retinopathy of prematurity. The participants were recruited from two self-help groups for the blind. Given our relatively complex reasoning tasks, we tried to avoid any confounding of blindness with differences in intellectual abilities. For several reasons, however, this could only be done unsystematically by asking the persons in charge if they knew of any other cognitive handicaps. A review of the medical and psychological documentation was impossible for data privacy reasons, and we refrained from testing intellectual abilities with standard IQ tests because we were concerned that this might have long-term effects and could touch personally relevant topics. We also did not include adventitiously blind people, because reports from the literature (Kerr, 1983) and our own interviews indicate that such persons experience vivid visual images. For similar reasons, several other studies with congenitally totally blind participants also rely on reasonably small samples (Loomis et al., 1993; Loomis, Lippa, Klatzky, & Golledge, 2002). All participants gave their informed consent prior to their participation in the study.

Materials, design, and procedure

The materials and the design were identical to those in Experiment 1. One of the experimenters read the instructions to the participants. The participants were tested individually in a quiet room at the institutions, and they sat in front of a laptop that administered the experiment. The reasoning problems again were presented via headphones. Except for the two keys associated with "yes" and "no" and the spacebar, all other keys were removed from an external keyboard. Since little is known about reasoning and blindness, after the experiment the participants were interviewed about the strategies that they applied to solve the problems.

Results and discussion

The second row of Table 2 presents the mean latencies and correct responses to the three sorts of relational inference. Overall, the blind participants responded correctly to 76.2 % of the inferences. Since again there was no significant difference between accepting valid conclusions (76.7% correct) and rejecting invalid conclusions (75.8% correct), we pooled the results from these conditions. The analysis of accuracy data shows no significant difference between the three sorts of relation. The visual relations tended to result in more correct responses than did the other sorts of problem, but the ANOVA does not show a significant difference in reasoning accuracy between the three sorts of problem, $F(2, 18) = 0.36$, $p = .70$, $\eta_p^2 = .039$. Likewise, none of the single contrasts revealed a significant difference: visual versus control, $F(1, 9) = 2.38$, $p = .63$, $\eta_p^2 = .026$; visuo-spatial versus control, $F(1, 9) = 0.70$, $p = .79$, $\eta_p^2 = .076$; visuo-spatial versus visual, $F(1, 9) = 0.74$, $p = .41$, $\eta_p^2 = .076$. In the response latencies, there was also no difference between the three sorts of relation, $F(2, 18) = 1.27$, $p = .31$, $\eta_p^2 = .124$, and there was no significant difference between visual and control relations, $F(1, 9) = 1.63$, $p = .24$, $\eta_p^2 = .153$, between visuo-spatial and control relations, $F(1, 9) = 0.90$, $p = .37$, $\eta_p^2 = .091$, and between visual and visuo-spatial relations, $F(1, 9) = 0.879$, $p = .37$, $\eta_p^2 = .089$.

Although the interview method has severe limitations, it can provide some clues as to how the congenitally blind participants solved the problems (or at least think that they did). In fact, all participants reported having used a purely spatial strategy for solving the reasoning problems. They often reported having presented the animals of the reasoning tasks on a vertical scale with, for instance, "dirtier" or "cleaner", or "smarter" or "dumber" as the poles of the scale. When we asked them explicitly about the role of "visual images", they consistently denied such visual experiences. Interestingly, however, for the tasks with "cleaner" and "dirtier" some of the participants, described having "imagined" haptic or tactile sensations: for instance the pelts of their pets or teddies.

What do these findings mean for our hypothesis concerning the role of visual imagery in reasoning of the congenitally totally blind? On the one hand, we tested only a relatively small number of blind participants and thus obtained a rather low test power. This means that our null-effect must be interpreted with caution. On the other hand, performance of the blind participants did not even show a trend that was similar to the sighted. In fact, the visual inspection of the data points in an opposite direction. The blind were slightly faster with the visual problems, although this difference is not statistically significant.

The findings shed new light on the role of visual and spatial representations in reasoning. It is reasonable to assume that the mental representations of persons who are blind from birth are different from those of sighted persons, because 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 individuals showed almost the same pattern of response times depending on imagined distance, imagined size, and so on. 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 individuals did not. 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 as do the visual images of the sighted. Obviously, people who are blind from birth do not construct visual mental images, but they are able to construct and employ spatial representations. In fact, 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, the reports agree with the experimental findings: The blind are able to use spatial representations without being distracted 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 visual environment and the mental activity of envisaging a visual mental image. To rule out this explanation, the participants in the third experiment 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, blindfolded individuals should also be resistant to the impedance effect of visual relations—much as the congenitally blind people are. If, on the other hand, 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 found in Experiment 1.

Methods

Participants

We tested 30 sighted undergraduate students of the University of Oldenburg (mean age 23.3 years; 18 female, 12 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 those in Experiments 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 90.6% correct responses, and there was no significant difference between accepting valid conclusions (90.2% correct) and rejecting invalid conclusions (91.4% correct). The data were pooled again. The ANOVA showed a reliable difference in accuracy across the relations, $F(2, 58) = 3.71$, $p < .04$, $\eta_p^2 = .114$, and the predicted linear trend over the three sorts of relation (visual < control < visuo-spatial) was significant, $F(1, 29) = 4.39$, $p < .04$, $\eta_p^2 = .132$. The single differences between visual and control relations, $F(1, 29) = 5.80$, $p < .03$, $\eta_p^2 = .167$, and visual and visuo-spatial relations, $F(1, 29) = 4.39$, $p < .04$, $\eta_p^2 = .132$, were also significant. The response latencies showed that problems consisting of visual relations were solved more slowly than those with control relations, which in turn were slower than the problems with visuo-spatial relations. The main effect across the three types of relation, $F(2, 58) = 4.22$, $p < .02$, $\eta_p^2 = .127$, and the linear trend, $F(1, 29) = 7.012$, $p < .02$, $\eta_p^2 = .195$, were statistically significant. The pattern of performance in the blindfolded participants was almost identical to that of the sighted participants in Experiment 1. There was again the trend visual relations > control relations > visuo-spatial relations in the latencies, and visual relations resulted in more errors than did the other two sorts of relation. These data reveal that the visual and spatial characteristics of the relations 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.

OVERALL ANALYSIS OF THE VISUAL-IMPEDANCE EFFECTS

The three experiments differed mainly in having different groups of participants. In all three experiments, the imageability of the relations was used as a within-subjects factor, and we demonstrated that sighted participants show a decrement in performance with visual relations compared to the other relations, whereas the congenitally blind group did not differ across the different sorts of relation. We did not treat the experiments as a single study with the three different groups of participants as a between-subjects factor, because the experimental set-ups were not identical, and a conjoint analysis would result in problems with the inhomogeneity of variance. However, a direct interaction between the three groups of participants and the different sorts of relation would provide additional support for our account. Therefore, we computed a post hoc ANOVA with the three sorts of relation as a within-subjects factor and the three experiments as a between-subjects factor. In this way, it is possible to estimate if the pattern of performance is different for blind and sighted participants. Figure 1 summarizes how the imageability of the relations (visual, control, visuo-spatial) affected reasoning accuracy

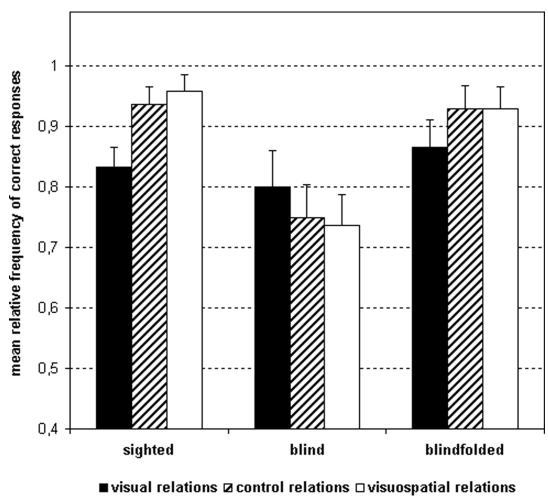

Figure 1. *Mean relative frequency of correct responses across the three groups of participants. In sighted and blindfolded participants visual relation resulted in significantly more errors than in the congenitally totally blind participants. Results for the blind participants show the opposite trend, although it is statistically not significant. Error bars indicate the standard error of the mean.*

in the three groups of participants. As indicated by the single experiments, sighted and blindfolded participants indeed show a significantly different pattern of performance across the three groups of relation. The mean number of correct responses was lower for the visual relations than for the control relations in the sighted, whereas the blind did not show this visual-impedance effect. This observation is supported by the ANOVA, which did not reveal a reliable effect of the three sorts of relation across the three experiments, $F(2, 122) = 2.11$, $p = .13$, $\eta_p^2 = .033$, but did reveal a significant interaction between experiment and the sort of relation, $F(4, 122) = 2.69$, $p < .03$, $\eta_p^2 = .081$. Thus, the pattern of performance across the three sorts of relation is reliably different for blind and sighted participants. The response latencies showed a similar pattern of results (Figure 2). Sighted (nonblindfolded and blindfolded) responded more slowly to the problems based on visual relations than to the other sorts of problem. The blind participants, in contrast, did not show this effect. In the ANOVA, the differences across the three sorts of relation were not significant, $F(2, 122) = 2.72$, $p = .07$, $\eta_p^2 = .043$, but there was again a significant interaction between experiments and the sort of relation, $F(4, 122) = 2.64$, $p < .04$, $\eta_p^2 = .08$, indicating that the performance across the three sorts of relation is different for blind and sighted participants.

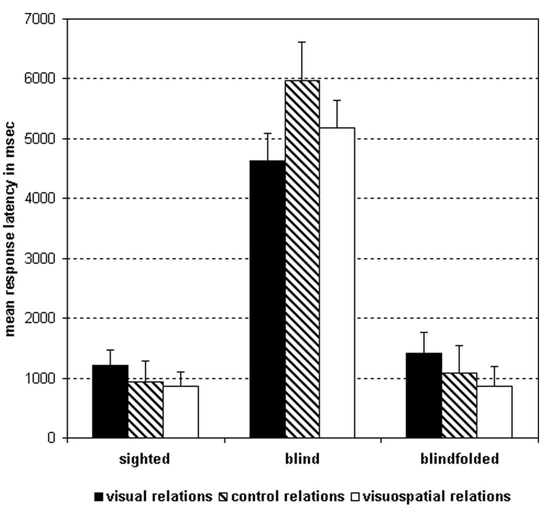

Figure 2. *Mean latencies for correct responses across the three groups of participants. In sighted and blindfolded participants visual relation resulted in significantly longer response times than those in the congenitally totally blind participants. Results for the blind participants do not show this impedance effect. Error bars indicate the standard error of the mean.*

The findings from the ANOVA with the three experiments as a between-subjects factor are also supported by two additional ANOVAs in which data from Experiments 1 and 2 are directly compared, and in which data from Experiments 1 and 3 are directly compared. The first analysis shows a significant difference between sighted and blind participants in terms of accuracy, $F(2, 64) = 4.51$, $p < .02$, $\eta_p^2 = .12$, and in terms of response latencies $F(2, 64) = 3.83$, $p < .03$, $\eta_p^2 = .11$. The second analysis confirms a significant difference between the blindfolded sighted and blind participants in terms of response times, $F(2, 76) = 4.31$, $p < .02$, $\eta_p^2 = .10$, and in terms of accuracy, although the latter difference felt short of significance, $F(2, 76) = 2.35$, $p = .10$, $\eta_p^2 = .058$.

GENERAL DISCUSSION

The starting point of our study was the distinction between visual and spatial modes of representation in reasoning. Previous studies enabled us to identify visuo-spatial 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 difficult to envisage spatially, and control relations, such as *better–worse*, which are difficult to envisage either visually or spatially.

In the present experiments, we tested a group of sighted participants, a group of congenitally totally blind participants, and a group of blindfolded participants with normal vision. For both the sighted and the blindfolded participants, the visual relations significantly impeded the process of reasoning in terms of both accuracy and time needed to verify the conclusion. The participants who were blind from birth, however, were not affected by the ease with which the verbal relations could be visualized: They showed the same reasoning performance across all three types of problem.

Given the present findings, a theory that relies on visual imagery as the medium for reasoning is implausible, because individuals can reason about relations that they cannot visualize. Moreover, such a theory would predict that increasing the ease with which a relation can be visualized would increase performance—the precise opposite of our present results. One might 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 with each other (Logie, 1986, 1995; Logie & Marchetti, 1991; Quinn & McConnell, 1996). Our third experiment with the blindfolded participants, however, clearly falsifies this hypothesis.

The most plausible explanation for the pattern of results is that reasoning is typically based on spatial representations. The initial idea was introduced by Huttenlocher (1968) and was further elaborated in the mental models theory of reasoning (Johnson-Laird, 1983; Johnson-Laird & Byrne, 1991). Within the mental model theory, linguistic 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 nonlinguistic 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 may not account for visual details such as colours, 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 (cf. 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, 2002). Likewise, a visual relation, such as *dirtier than*, can elicit a vivid visual detail, such as an animal caked with mud, which is irrelevant to an inference.

Our data, however, yielded a striking result contrary to the orthodox hypothesis that visual images support reasoning. In fact, visual relations impeded reasoning of the sighted participants. One possible explanation is that reasoning could interfere with visual mental imagery. Yet this hypothesis can be rejected, because spatial tasks interfere little with visual working memory tasks (Klauer & Zhao, 2004). Moreover, Knauff et al. (2004) showed that reasoning with relations is not disrupted by visual tasks. The most reasonable account for the impedance effect is that reasoning is based on spatial representations, but visual relations spontaneously elicit visual imagery that is not pertinent to reasoning. Accordingly, the spatial information must be retrieved from the visual image in order to construct the appropriate spatial mental model for making the inference. It is conceivable that all reasoning—and even reasoning with the control relations—is based on such spatial models. It follows from this hypothesis that visual images might be constructed during the processing of the premises with visual relations, but the later processes must be based purely on spatial representations and processes. This is in accordance with results from text comprehension showing that visual representations are routinely and immediately activated during word and sentence comprehension (Glenberg, 1997; Stanfield & Zwaan, 2001; Zwaan, Stanfield, & Yaxley, 2002). It is also in agreement with the results from neuroimaging studies in which only highly visual premises resulted in activity in visual brain areas but subsequent processes activated areas of the dorsal stream—that is, part of the where-pathway (Fangmeier, Knauff, Ruff, & Sloutsky, 2005; Knauff, Fangmeier, Ruff, & Johnson-Laird, 2003). These findings demonstrate that human reasoning proceeds in separable phases and that visual brain areas can be involved in premise processing and the construction of initial visual images, but the reasoning process itself relies on more abstract spatial representations held in spatial brain areas. However, to extract the relevant spatial information takes longer and is more error prone. If, in contrast, the reasoner is not biased towards such "detours", as is the case with visuo-spatial and control relations, reasoning proceeds with fewer errors and faster than with other sorts of content. The blind participants, however, did not show this visual-impedance effect. This provides additional support for the spatial account of reasoning. People who are blind from birth do not tend to use visual mental images, but they are able to construct and to employ spatial representations. For this reason, they are not sidetracked by irrelevant visual images and thus perform relatively better than sighted persons with visual relations.

There are, however, some ambiguities in the data from the blind individuals. First, the data are in line with other studies that compared blind and sighted people on a large variety of visuo-spatial 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 91.3% of the inferences correctly, but the blind participants solved only 76% correctly. The sighted needed 1.01 seconds on average to respond to a problem; the participants who were blind from birth needed 5.3 seconds. The dominant approach to explain such findings runs somewhat counter to our own account. Many researchers view it as a *visual imagery deficit* of the congenitally blind. Haptics or auditory perceptions certainly also lead to spatial representations, but, the researchers argue, these representations might be suboptimal compared to vision-based representations (a recent discussion can be found in Fleming, Ball, Collins, & Ormerod, in press). From this view, our blind participants have shown worse performance because they are worse at 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.

Another possible explanation for the overall deficit in reasoning is that the differences between non-blind participants (in both blindfolded and non-blindfolded conditions), and the congenitally-blind people might not be solely due to differences in visual mental imagery. Instead, the differences could also be due to other discrepancies, e.g., if the congenitally blind participants differ from non-blind students in terms of working memory capacity or other cognitive abilities. This account cannot completely be ruled out by the present data, in particular because psychology students in Germany are highly selective, and so they were certainly above average in intelligence. Even though this is a possible explanation, we are convinced that it was good not to use IQ tests that might have had long-term effects on the blind peoples' personality or at least would have prevented them from participating in the study. Moreover, we think that this explanation alone does not account for our data given the specific pattern of results and that intellectual differences are usually also not reported in the literature on visual impairment and blindness (cf. Fleming, Ball, Collins, & Ormerod, in press).

From our point of view, a more reasonable explanation for the overall deficit in reasoning of the blind individuals is probably due to a complex combination of symptoms. Most of our congenitally blind participants suffered from a syndrome called retinoophtalmopathia (ROP). ROP appears in individuals that were born prematurely and received too much oxygen in the incubator, resulting in damage to the retina. Several researchers stated that if oxygen injures the retina, areas in the brain that normally control specific spatial cognitive processes are likely to be injured too (Stuart, 1995). However, this does not result in an overall spatial deficit, as the aforementioned studies proved, but can affect highly specific spatial abilities. A number of studies with congenitally totally blind children and young adults support this assumption. Rieser, Guth, and Hill (1982), for example, found that early blinded and congenitally blind adults sometimes have problems updating spatial representations. In their own living rooms, they performed very well in pointing out the exact spatial positions of their furniture while standing at various points within the room. In the laboratory, however, they performed much worse in an analogous task. Rieser et al. argued that sighted persons always see spatial relations simultaneously changing as their own spatial position changes. Individuals who are blind from birth never experience such spatial changes instantly. Rieser et al. conclude that congenitally blind people are able to represent the spatial arrangement of objects, but have problems in integrating new information. This would fit well with the mental model theory that describes reasoning as a three-stage process in which the information from the premises is integrated into one unified representation, and this model is inspected and validated (Johnson-Laird & Byrne, 1991). These processes, which involve the integration and updating of spatial representations, are not yet understood in congenitally blind individuals, and it is an open question as to how the complex of symptoms of congenitally ROP-blind persons had a particular effect on reasoning performance. To answer this question, we will continue running experiments with blind participants and will try to compare participants with ROP to congenitally non-ROP blind participants.

A second critical aspect in our studies is that we did not use purely spatial relations—that is, 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 and Johnson-Laird (2002). However, we encountered some technical problems with these relations, and some colleagues doubt the existence of such relations altogether. Further studies will be needed to clarify this point. Moreover, the interviews with the blind participants might suggest using another sort of nonvisual relation. If a more general version of the impedance hypothesis is correct, then congenitally totally blind individuals should tend to construct vivid tactile or haptic mental images for relations such as softer–harder, smoother–rougher, colder–hotter, and so on. If so, such tactile or haptic relations should then also have an impeding effect on the reasoning of the congenitally totally blind individuals.

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 visuo-spatial relations, then reasoning proceeds smoothly. However, if the content yields visual images that are irrelevant to an inference, as it does with visual relations, then reasoning of sighted persons takes reliably longer and is more vulnerable to errors. People who are blind from birth are immune to such impedance effects, since they do not tend to use disrupting visual images.

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