



TMS applied to V1 can facilitate reasoning

Kai Hamburger¹ · Marco Ragni^{1,2} · Harun Karimpur¹ · Imke Franzmeier² · Florian Wedell¹ · Markus Knauff¹

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Abstract

Visual mental imagery is the subjective experience of seeing objects or events in front of the ‘inner eye’, although they are not actually present. Previous research indicates that (1) visual images help to remember what has been experienced in the past or when objects need to be inspected or manipulated, and (2) visual images are correlated with neural activity in early visual cortices, demonstrating a possible overlap between visual imagery and visual perception. However, recent research revealed that visual imagery can also disrupt cognitive processes and impede thinking. In this transcranial magnetic stimulation (TMS) experiment, participants had to solve relational reasoning problems that varied in their imageability (easy or difficult to visualize as a mental image). While solving the problems, eight 10 Hz pulses were either applied to primary visual cortex (V1) or a control site (Vertex). Our findings suggest a causal link between mental imagery, primary visual cortex, and reasoning with visual problems. Moreover, participants exhibited much lower error rates when TMS was applied to V1. We conclude that the disruption of visual images in primary visual cortex can facilitate reasoning.

Keywords Mental imagery · Reasoning · Primary visual cortex · Transcranial magnetic stimulation (TMS)

Introduction

Visual mental images represent a vital part of human cognition and an important research topic in cognitive psychology and the neurosciences. One way to think about mental imagery relies on people’s common report of experiencing their thinking as ‘seeing with their inner eye’ or as having a ‘picture-like experience’. We are all familiar with this subjective experience that is commonly accepted in the cognitive sciences. However, another way to think about mental imagery goes beyond the introspective experience and considers visual images as something ‘real’ in the human brain playing a causal role in our mental activities. This research was triggered by several studies from the early years of cognitive psychology. Perhaps the most impressive illustration of the role of visual mental images in human cognition was the seminal experiment by Kosslyn et al. (1978), who asked

participants to memorize a map of a fictitious island. In a later memory test participants had to imagine a dot flying from one object to another object on the map. If there was a greater distance between objects on the map, participants required more time to mentally move from one object to another. In memory research, such results were taken by some researchers as evidence that visual mental images are a distinct kind of mental representation, which—despite some differences (e.g., Chambers and Reisberg 1985; Slezak 1991)—are similar to representations resulting from the actual stimulation of the retina (e.g., Kosslyn et al. 2001; Slotnick et al. 2012; Pearson et al. 2015).

However, the first experiments on mental imagery did not come from memory research but from the study of human reasoning (Störring 1908). Another classical study on imagery in reasoning was conducted by De Soto et al. (1965), who investigated relational problems, such as

Ann is taller than Beth	(Premise 1)
Cath is shorter than Beth.	(Premise 2)
Who is tallest?	(Conclusion)

✉ Kai Hamburger
kai.hamburger@psychol.uni-giessen.de

¹ Department of Psychology, Experimental Psychology and Cognitive Science, University of Giessen, Otto-Behaghel-Str. 10F, 35394 Giessen, Germany

² Cognitive Computation Lab, University of Freiburg, Georges-Köhler-Allee 52, 79110 Freiburg, Germany

These authors claimed that reasoners represent the three given people from the premises in a visual image and then ‘read off’ the conclusion by inspecting this image. Following this idea, several authors assumed that if reasoning relies on

visual mental images, then reasoning with materials that are easy to visualize should be easier and accompanied by better performance than reasoning with materials that are hard to visualize. Yet, the evidence is equivocal. Some researchers reported a facilitating effect of imageability (Clement and Falmagne 1986; Huttenlocher 1968; Pearson et al. 1999), while others did not find evidence for the role of visual imagery in human reasoning (Johnson-Laird et al. 1989; Newstead et al. 1986; Richardson 1987; Sternberg 1980). Recent studies demonstrated that visual mental images can even impede reasoning. Participants often need more time to solve the problems and make more errors if they visualize the content of a reasoning problem (Bacon and Handley 2010; Bacon et al. 2007; Gazzo Castañeda and Knauff 2013; Johnson-Laird 2006; Knauff and Johnson-Laird 2002). Additionally, brain imaging studies showed that the visual images during reasoning are correlated with neural activity in primary and secondary visual cortex (Knauff et al. 2003), that people's eye-movements during reasoning correspond to visual scanning processes (Körner and Gilchrist 2004; Ragni et al. 2009; Sima et al. 2010), and that psychotropic drugs (e.g., benzodiazepine) slow down reasoning processes containing visual images (Pompéia et al. 2007). Interestingly, congenitally totally blind people who do not experience visual images (e.g., Arditi et al. 1988) are not disrupted by problems that are easy to visualize for people with normal vision. Thus, blind people perform better on highly visual problems than normal sighted people (Knauff and May 2006).

Therefore, do visual mental images play a causal role in human reasoning? Do we need visual mental images to draw inferences and to reason accurately? For many researchers the answer to this question is 'yes'. They argue that "it is clear that imagery plays a key role in reasoning" (Kosslyn 1994, p. 404). Other researchers' answer would be 'no' because they overall deny the role of visual imagery for our cognitive abilities (e.g., Pylyshyn 1973, 1981, 2002). For these researchers, visual mental imagery is a mere epiphenomenon playing no causal role in reasoning (e.g., Pylyshyn 1981, 2003, 2006).

We disagree with both positions. On the one hand, images may indeed play a key role in reasoning. Thus, they are not mere epiphenomena. On the other hand, we think about visual images differently than what standard imagery theorists assume. They are causally relevant, but not in the sense that they do help to reason. For us, visual images have a causal effect because they can hinder the process of thinking. This approach is elaborated in more detail in Knauff (2013).

The present research is the first transcranial magnetic stimulation (TMS) study on the role of visual images in human reasoning. Since we are particularly interested in the cortical basis of visual imagery and relational reasoning, we start with summarizing the current state of research in both

fields. Based on this previous research, we formulate our hypotheses on the effects of TMS on visual imagery during inferential reasoning. In the main section of the paper, we report the TMS study in which we tested these hypotheses on the causal links between primary visual cortex, mental imagery, and reasoning. Finally, we challenge the visual theory of reasoning and discuss some alternative ideas.

Cortical basis of visual imagery and relational reasoning

Classical behavioral studies on mental scanning (Kosslyn et al. 1978) demonstrated that visual mental images play an important role in human cognition. About two decades later, visual mental imagery was also one of the first topics studied with modern brain imaging methods such as functional magnetic resonance imaging (fMRI) and positron emission tomography (PET) (Bartolomeo 2008; Bly and Kosslyn 1997; Cohen et al. 1996; Kosslyn 1994; Mellet et al. 1998). The most influential research line in this area posits that early visual cortex is not only involved in visual perception but also used to support representations during visual imagery. Largely driven by the work of Kosslyn, research suggests a functional role of the primary visual cortex (V1, BA17) in visual imagery. Early visual cortex supports depictive, pictorial representations—retinotopically organized—rather than descriptive representations during the perception process. Therefore, it may be assumed that in visual imagery this part of the cortex also holds a functional role. If this assumption proves to be correct, then the early visual cortex is not only crucial for visual perception but also constitutes a 'visual buffer' that can be activated 'top-down' by memory retrieval or processes of thought (Ishai 2010; Knauff 2013; Kosslyn 1980, 1994).

Several studies of the last decades support this account and show that the visual cortex is activated during mental imagery. For instance, Kosslyn et al. (1993) found that the V1 is activated when participants mentally rotate letters. Kosslyn et al. (1997) found neural activity in V1 when people manipulate visual images of objects. Moreover, if participants imagined differently sized letters, the larger letters activated a larger region of V1, whereas the smaller letters activated a smaller region (Kosslyn et al. 1993). An important result comes from a combined PET and repetitive TMS (rTMS) study, where participants had to compare properties (e.g., relative length) of sets of stripes: When patterns of stripes were visualized, the PET showed an activation of V1, and the rTMS results indicated that this activation is causally relevant for processing visual mental images (Kosslyn et al. 1999). In addition, under TM stimulation, performance degraded and response times increased accordingly in both conditions tested, perception and imagery. These and other

findings on the connection between imagery and V1 have been discussed in a number of detailed reviews by Kosslyn's research group (Kosslyn et al. 2001; Kosslyn and Thompson 2003; Pearson et al. 2015).

The neural basis of inferential reasoning is another important topic of the cognitive neurosciences. Again, this strain of research started from behavioral experiments in cognitive psychology (e.g., De Soto et al. 1965; Huttenlocher 1968; Störing 1908) and later extended into brain research (e.g., Goel et al. 1998; Knauff et al. 2002). An overview about the state of research in the field is given in Goel et al. (2017). Here we just briefly summarize what is pertinent to our present research. First, it is now pretty clear that relational reasoning (on which we focus here) significantly differs from conditional and syllogistic reasoning, not only in terms of the underlying cognitive processes, but also in terms of the involved brain circuits (e.g., Coetzee and Monti 2018; Goel et al. 2000; Noveck et al. 2004). Very roughly speaking, the cortical network of relational reasoning covers areas in the prefrontal and the parietal cortices (Hobeika et al. 2016; Prado et al. 2011; Vendetti et al. 2015). A more recent analysis of relational reasoning depending on the characteristics of the task can be found in a meta-analysis by Wertheim and Ragni (2017). Second, there is also evidence that the complexity of the relation (e.g., binary, tertiary, and quaternary relations) is manifested in the brain; the more complex the relation is the more activity can be found in frontal brain areas, a result that agrees with findings from studies on patients with damage to the frontal cortex (Andrews et al. 2014). In addition to that activation in visual areas has been demonstrated (Knauff et al. 2002). Third, it has also been shown that TMS can disrupt inferential reasoning. Tsujii et al. (2011) showed that TMS can disrupt syllogistic reasoning and our own group showed that TMS can disrupt uncertain reasoning with spatial relations (Ragni et al. 2016). In this study, TMS was applied to the right superior parietal lobe and had a disrupting effect on reasoning with spatial descriptions that could be interpreted in more than one way.

Two studies on the role of visual imagery in reasoning about relations were conducted by Knauff and Johnson-Laird (2002) and Knauff et al. (2003). The first article reports a set of behavioral studies, while the second paper reports a brain imaging study using the same experimental materials. As we used the same relational reasoning problems in the present research, we describe these materials now in more detail. In Knauff and Johnson-Laird (2002), we started with carrying out a norming study to determine whether the ease of visualizing a relation between different entities might be independent of the ease of forming a spatial representation of the relation. 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”. Participants rated the ease of forming a visual image and a spatial representation on a scale ranging from 1 (very difficult) to 7 (very easy). The ratings showed that the relations do differ in the rated ease of forming both images and spatial representations of them. For example, on average, the visuo-spatial relation “above–below” was rated with a 5.3 on the visual rating scale and with a 5.4 on the spatial rating scale. The visual relation “cleaner–dirtier” was rated with a 5.1 on the visual rating scale but only with a 1.6 on a spatial rating scale. However, we were not able to find purely spatial relations, and thus concluded that the use of two separate ratings might not be sensitive enough to reveal differences between visual and spatial relations. Thus, in a second study, the participants rated on a single bipolar 7-point scale whether each relation evoked a visual or, else, a spatial representation. The poles of the scale were labeled visual and spatial, respectively. The instructions stated that a visual representation is a vivid mental image that may include concrete people, objects, colors, or shapes and that it can be similar to a real perception, whereas a spatial representation is a more abstract layout that represents something on a scale, an axis, or a spatial array. We coded the spatial pole as -3 and the visual pole as $+3$. With this study, we were indeed able to identify two pairs of spatial relations “ancestor-of–descendant-of” (-0.9) and further-north–further-south (-2.7) which reliably differed from the two visual relations. From these data we concluded that it might be not so easy to distinguish some sorts of relations introspectively, but that an appropriate method and an aggregation over a group of participants makes this distinction possible to a sufficient extent. Moreover, we particularly reasoned that it is empirically possible to distinguish purely visual relations such as “cleaner–dirtier” from other sorts of relations, which might have a visual component too, although probably to a lesser extent, or probably intermixed with other spatial or even more abstract characteristics. In any case, the visual relations seem to be “purely” visual, while the other sorts of relations are less purely visual in nature. We then conducted several reasoning experiments with these relations and found that people reasoned significantly slower and made more errors with the visual relations than with the other sorts of relations. Based on these findings Knauff et al. (2003) conducted an fMRI study with the same types of problems and found that only reasoning with purely visual relations activated areas of primary and secondary visual cortices (Knauff et al. 2003), while reasoning with all other relations was just accompanied by activity in parietal brain areas. Thus, on the behavioral level visual images resulted in impeded reasoning performance, and on the cortical level this was accompanied by activity in primary visual cortex.

Therefore, what happens if it is more difficult to construct visual images during reasoning in primary visual cortex? TMS is a helpful method to answer this question, as it allows researchers to facilitate or disrupt the neural processing in a well-defined cerebral area. This is particularly relevant for visual processing where studies have found both, impairments and facilitations when TMS was applied to the visual cortex (Cattaneo et al. 2009, 2011). More detailed analyses then showed that a facilitation usually results from a TM stimulation intensity below the individual threshold of the participants, while a stimulation intensity above the individuals' threshold typically leads to a disruption of neural processing in the stimulated cortical areas (Romei et al. 2016; Silvanto and Cattaneo 2017). In our experiment, we applied TMS to the primary visual cortex with a stimulation intensity that was slightly above threshold and thus should disrupt neural activity in primary visual cortex and in turn peoples' ability to construct visual images.

Based on the previous findings on the connection between visual imagery and reasoning, we here investigate the following hypotheses: First, we assume that TM stimulation of V1 should affect reasoning accuracy only in terms of errors but not in reasoning speed. This prediction is based on previous TMS studies showing disruptive effects of TMS just on reasoning accuracy but not on latencies (Ragni et al. 2016). Second, and most importantly, we predict that participants should exhibit lower error rates when TMS is applied to V1. This prediction is based on our assumption that visual images can hinder reasoning (Knauff 2013). Our third hypothesis is that the other kinds of problems are, if at all, only mildly affected by the TM stimulation of V1. The reason for this is that V1 is not or only minimally involved in processing these problems and stimulation should therefore have no reliable impact.

TMS experiment

Methods

Participants

Fourteen students of the University of Freiburg were examined. Each participant provided informed written consent. Participation was voluntary and compensated with 10 €. The study was conducted in accordance with the Declaration of Helsinki (1964; in its latest version) and was approved by the Ethics Committee of the University Clinic Freiburg. To control for any adverse reaction to TMS, we checked each participant prior to the experiment using the TMS-Screening Questionnaire (Keel et al. 2001). A T1-weighted MRI scan was obtained for each participant to allow a precise localization of the region of interest (ROI) and the exact TMS coil

positioning. Four participants were excluded due to technical errors. Thus, data of ten participants were analyzed (three females, seven males; mean age 22.8 years; range 19–25). Sack et al. (2009) showed that this number of participants is sufficient for the TMS coil-positioning approach that we used (see “[Procedure](#)” and “[Localization of V1](#)”).¹

Material

Participants had to solve 32 relational reasoning problems and four practice trials (in German). The problems were taken from the studies by Knauff and Johnson-Laird (2002) and Knauff et al. (2003) (see Table 1). As we described above, these studies resulted in four sorts of relations, but not all of them were easy to distinguish. The clearest difference was between purely visual relations such as “cleaner–dirtier” on the one hand, and the other sorts of relations which are not purely visual on the other. In the following, we refer to inferences that were based on the visual relations as purely visual problems, and to inferences with the other sorts of relations as other problems.

Each problem consisted of two premises containing three objects. The objects used in the premises were animals (ape, cat, dog). To solve a problem, participants had to indicate whether the conclusion was true (valid) or false (invalid). Table 1 provides examples for the different problem types (also see: Knauff and Johnson-Laird 2002). Problem types and validity were counterbalanced and pseudorandomized across participants: eighteen problems were presented during TM stimulation of V1 and the other eighteen while TMS was applied to Vertex. The Vertex is a control site and refers to the upper surface of the head, where the four bones of the skull come together; there, no critical brain tissue is to be stimulated (e.g., Franzmeier et al. 2012) and it previously showed no effect for relational problems (Ragni et al. 2016). Both blocks (V1 or Vertex stimulation) consisted of an equal amount of valid and invalid problems for each problem type.

Procedure

The study was conducted in a single session at the TMS-Lab of the Neurocenter Freiburg (University Hospital). First, the

¹ In Sack et al. (2009) a power analyses revealed that in the fMRI-guided neuronavigation approach $n=5$ participants are sufficient to reveal a significant behavioral effect; this number of necessary participants increases to $n=9$ when employing MRI-guided neuronavigation—that is what we use in our experiment with a final sample of $N=10$ —it increases to $n=13$ in case of TMS based on group Talairach coordinates, and to $n=47$ with even weaker localization methods. The tasks were different from ours, but the results show that the number of participants in our study is sufficient for TMS studies in which MRI-guided neuronavigation is used for TMS coil positioning.

Table 1 Example problems for each relational type

Problem type	Premises		To-be-validated conclusion	Solution
	Premise 1	Premise 2		
Purely visual problems	The dog is cleaner than the cat	The dog is dirtier than the ape	The cat is dirtier than the ape?	Valid
	The cat is thinner than the dog	The dog is thicker than the ape	The ape is thicker than the dog?	Invalid
Other problems (visuo-spatial, spatial, and abstract problems)	The dog is worse than the cat	The dog is better than the ape	The cat is better than the ape?	Valid
	The cat is smarter than the dog	The dog is dumber than the ape	The ape is dumber than the cat?	Invalid
	The dog is in the back of the cat	The dog is in front of the ape	The cat is in front of the ape?	Valid
	The cat is below the dog	The dog is above the ape	The ape is above the cat?	Invalid
	The dog is further south of the cat	The dog is further north of the ape	The cat is further north of the ape?	Valid
	The dog is ancestor of the cat	The ape is descendant of the dog	The cat is descendant of the ape?	Invalid

The first column shows the relational type of the given problem

With columns two, three and four both premises and the to-be-validated conclusion are shown. The last column shows whether the problem leads to a valid (true) or invalid (false) solution

participants were required to fill out a short demographics questionnaire. After reading the instructions, each participant's individual intensity level for the transcranial magnetic stimulation was determined (see “TMS Protocol”). In half of the participants, TMS was applied to V1 in the first block and to the control site (Vertex) in the second block. In the other half of the participants, the order of the two conditions was reversed. Stereotactic navigation constantly monitored the position of the coil. Upon a button press to start each individual block, the two premises and the to-be-evaluated conclusion were shown in succession: after an initial fixation cross the first premise was shown for 3 s, then the screen remained blank for 1.5 s, then the second premise was shown for 3 s. The stimulation with TMS took place during the next 1.5 s blank screen phase. It started 200 ms after the screen became blank and had a duration of 800 ms. During these 800 ms a sequence of eight 10 Hz pulses was applied. Then the to-be-evaluated conclusion was shown for 4.5 s (Fig. 1). Participants had to evaluate the conclusion by pressing a green button for true or a red button for false on a CEDRUS-response box. The conclusion disappeared when a participant had pressed a button or after the 4.5 s. Participants were instructed to evaluate the conclusion as quickly but also as accurately as possible. A short break was introduced after the first block. During the break, the TMS coil was re-positioned onto the second stimulation site. The experiment, which on average had a duration of 30 min, was closed with a short debriefing.

TMS Protocol

A MagPro X100 (Magventure, Denmark) TMS device, consisting of a figure-of-eight coil for the stimulation (rTMS) was used for the experiment. It has repeatedly been

demonstrated that a frequency of 10 Hz modulates cognitive processes consistently (e.g., Devlin et al. 2003; Gough et al. 2005; Hartwigsen et al. 2010; for an overview on TM stimulation please see; Walsh and Pascual-Leone 2003). Therefore, we applied eight 10 Hz biphasic pulses (800 ms) throughout the experiment. The stimulation was triggered 200 ms after the presentation of the second premise. Pulses were placed to the primary visual cortex (V1, BA 17) and as a baseline-measure to the control site (Vertex). To determine the individual threshold of the participants we initially planned to use the threshold at which participants reported to start experiencing phosphenes, that is, to see light without

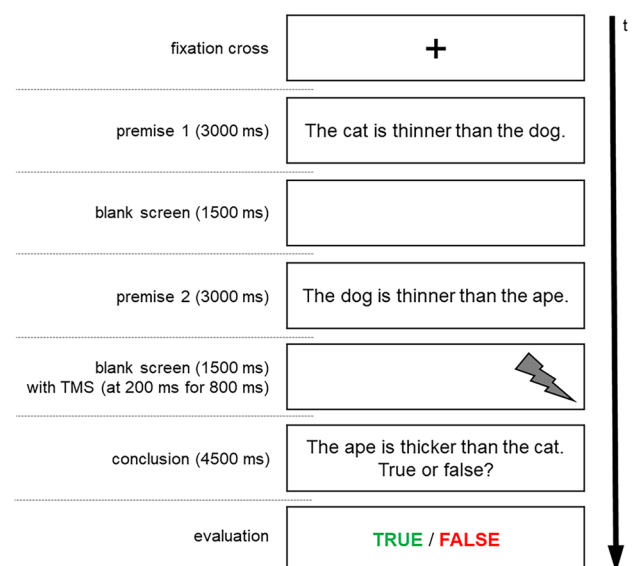


Fig. 1 Sequence and timing of a single trial; the flash-icon indicates that the TMS pulse was applied during the presentation of this screen

light actually entering the eye. However, in a pilot run, one of the authors experienced that as rather unpleasant and even reported headache after the study. We therefore decided that it is better not to use this method in our experiment. Instead, we measured motor-evoked potentials (MEP) to use the individual motor threshold (MT), that is, the lowest stimulation intensity eliciting twitches in the left hand. Early studies by Stewart et al. (2001) argued that using phosphene thresholds (PT) is more appropriate for visual TMS studies than MT. However, more recent experiments by Deblieck et al. (2008) demonstrated a significant correlation between PT and MT, which also justifies to use MT in visual TMS studies. Another advantage of MT is that it is more objective than PT, which mainly relies on peoples' report of seeing phosphenes. Thus far, there is no standardized and widely accepted methodology available for documenting the occurrence of phosphenes (Elkin-Frankston et al. 2010), while hand twitches can be seen by the experimenter. Based on the Maximum-Likelihood strategy for estimating motor thresholds (MTAT 2.0, <http://clinicalresearcher.org>), adaptive parameter estimation by sequential testing (PEST) procedures was used to determine the individual resting motor threshold (rMT). We defined a value slightly above 100% of the individual rMT as TMS stimulation intensity. The mean rMT of the ten participants was 35.4% (range 29–42%).

Localisation of V1

For every participant, a high-resolution structural MRI scan was available from a previous study collected with a 3-T Siemens TRIO scanner (Siemens, Erlangen, Germany). This ensured a precise positioning of the TMS coil onto the targeted brain region via stereotactic neuro-navigation. According to the Anatomy Atlas by Eickhoff et al. (2005) we extracted V1 as region of interest (ROI) based on the studies by Kosslyn and colleagues (e.g., Kosslyn et al. 1993, 1997). The ROI was stimulated during the experiment. We transferred the ROI-mask into individual space (MNI to individual) calculated from the participants MRI scan. Figure 2 demonstrates the localization of V1 (created with MARINA; Walter et al. 2003). To align the TMS coil and to monitor its position, we used stereotactic navigation (LOCALITE TMS Navigator, Germany). A flexible arm with ball joints fixated the coil during the experiment, while the head of the participants was stabilized with a head and chin rest.

Results

We first analyzed the response times, but did not find reliable differences between purely visual problems ($M=2845.29$, $SEM=327.22$) and the *other* problems ($M=2877.14$, $SEM=350.66$). This result is reflected by a two-factorial

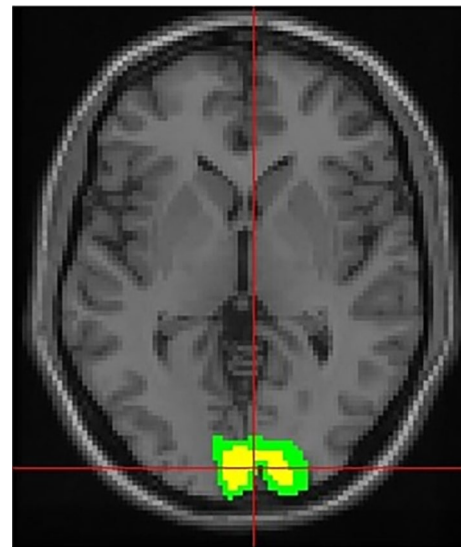


Fig. 2 Localization of the primary visual cortex (V1) for the TM stimulation; image shows a normalized structural brain image, colored areas indicate the region of interest (ROI)

Table 2 Descriptive statistics for the errors (in percent) for the stimulation sites primary visual cortex (V1) and the control condition (Vertex), split by problem type: purely visual problems versus other problems

Stimulation site and problem type		Errors in %	
		<i>M</i>	<i>SEM</i>
V1	Purely visual problems	10.00	4.08
	Other problems	29.17	6.60
Vertex	Purely visual problems	30.00	6.24
	Other problems	28.33	6.36

repeated measures analysis of variance (ANOVA) with both stimulation site and problem type as within-subject factors. There was neither a main effect of stimulation site [$F(1, 9)=0.001$, $p=.971$, $\eta_p^2=0.000$], nor a main effect of problem type [$F(1, 9)=0.056$, $p=.819$, $\eta_p^2=0.006$]. Then, we analyzed the mean error rates for the different reasoning problems under V1 and Vertex (control) stimulation. As can be seen in Table 2 and Fig. 3, there were no meaningful differences between purely visual problems and the other problems, $M_{\text{diff}} = 1.67$, 95% CI ($-9.14, 12.48$), $p=.735$, but with the purely visual problems participants made less reasoning errors under V1 stimulation than under Vertex stimulation, $M_{\text{diff}} = -20.00$, 95% CI ($-36.43, -3.57$), $p=.022$. The other problems did not show such an improvement of reasoning accuracy during V1 stimulation, $M_{\text{diff}} = 0.83$, 95% CI ($-16.36, 18.03$), $p=.915$. A preceding two factorial repeated measures analysis of variance (ANOVA) shows that the main effect of imageability was close to

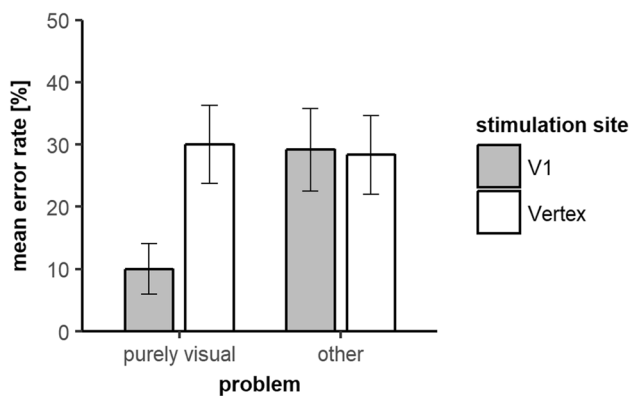


Fig. 3 Error rates in percent during stimulation of the primary visual cortex (V1) and the baseline stimulation (Vertex) for the purely visual problems (easy to imagine) and other problems; error bars depict the standard error of the mean

significance, $F(1, 9) = 4.788$, $p = .056$, $\eta_p^2 = 0.347$, while the main effect of stimulation site was not significant, $F(1, 9) = 2.106$, $p = .181$, $\eta_p^2 = 0.190$. Finally, we investigated the interaction between imageability and stimulation site. Here we found that a stimulation of V1 reduced error rates only in case of purely visual problems, while the other problems remained unaffected by the TMS, $F(1, 9) = 9.298$, $p = .014$, $\eta_p^2 = 0.508$. Moreover, pairwise comparisons showed that only under V1 stimulation participants made significantly less errors with purely visual problems, but not with the other problems, $M_{diff} = -19.17$, 95% CI $(-32.06, -6.27)$, $p = .008$.

Discussion

It is still not entirely clear how TMS affects cognitive processes (Romei et al. 2016; Silvanto and Cattaneo 2017). For instance, some studies showed that it facilitates visual processing (Cattaneo et al. 2009, 2011), while others found that peoples' ability to construct visual images is impeded by TMS (Kosslyn et al. 1999). In our study, we used an approach that most likely resulted in a disrupting effect on neural processing and thus on our participants' ability to use visual mental imagery to solve relational reasoning problems. Our starting point were previous studies on the connections between visual imagery, relational reasoning, and primary visual cortex (Gazzo Castañeda and Knauff 2013; Knauff and Johnson-Laird 2002; Knauff and May 2006; Knauff et al. 2003; Knauff 2013). In the present study, we wanted to go one step further by exploring the causal links between imageability, reasoning, and V1.

Our results show that people make fewer errors in reasoning with purely visual problems when TMS was applied to V1. In other words, reasoning performance gets better if the

construction of visual images is hindered by the disrupting effect of TMS. This is a novel finding that challenges the classical view that imagination helps people to reason accurately (Clement and Falmagne 1986; Huttenlocher 1968; Pearson et al. 1999). If reasoning is supported by visualization then the disruption of visual images in V1 should have resulted in lower reasoning performance. The opposite was the case in our study. People reasoned better without visual mental images.

Our findings are in agreement with previous findings from different research fields, e.g., studies with neurological patients that suffer from damages to the visual cortex. Typically, such people perform worse on visual memory tasks (e.g., Behrmann 2000). Yet, the opposite was observed in reasoning. In Knauff and May (2006), 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 blindfolded participants, visual imageability significantly impeded the process of reasoning in terms of both accuracy and reasoning speed. The participants who were blind from birth, however, were not affected by the ease with which the reasoning problems could be visualized. Most of these participants were born prematurely and suffered from a syndrome called retinopathy of prematurity (ROP) which is a side effect of too much oxygen in the incubator, resulting in damage to the retina and, as a consequence, visual brain areas, too (Stuart 1995). Interestingly, these participants showed the same reasoning performance across all types of problems. These results challenge the visual theory of reasoning but nicely fit with our TMS findings.

So, why do our participants perform reliably better with visual problems when in fact their ability to visualize was reduced? A possible explanation is that the TMS signal also had an effect on other brain areas relevant for reasoning. However, we do not think that this is a satisfactory explanation. An alternative account is related to the functions and malfunctions of visual images in reasoning (Knauff 2013). Several experiments have shown that visual images in V1 are routinely activated during word and sentence comprehension. These images are constructed even if participants did not receive any instruction to form visual images, and they can help to understand the text (Glenberg 1997; Sadoski 1985; Sadoski and Paivio 1994; Stanfield and Zwaan 2001; Zwaan et al. 2002). However, in our experiment, participants had not just to imagine the content of a text. They actively had to draw an inference which involves other cognitive processes. Is visualization necessary to perform such inferences? Not so, as previous experiments showed (Bacon and Handley 2010; Bacon et al. 2007; Gazzo Castañeda and Knauff 2013; Johnson-Laird et al. 1989; Johnson-Laird 2006; Knauff and Johnson-Laird 2002; Newstead et al. 1986; Richardson 1987; Sternberg 1980). Instead, it is possible that

reasoning relies on more abstract mental representations and processes. Several accounts are possible: first, the underlying cognitive processes could rely on language-based, syntactic processes and mental proofs of derivation (e.g., Adler and Rips 2008; Braine and O'Brien 1998; Hagert 1984; Rips 1994; van der Henst 2002). However, this account seems rather implausible for the relational inferences in our study (e.g., Coetsee and Monti 2018; Knauff 2013). Second, it is possible that humans use subjective probabilities to solve the inferences (e.g., Oaksford and Chater 2007). For instance, they could estimate the probabilities of dirty or smart dogs, cats, and apes, and then use this information to compute other probabilities. Currently, this probabilistic approach is quite popular in reasoning research (e.g., Griffiths et al. 2012; Oaksford and Chater 2007, 2017), but even supporters of the approach consider it implausible for relational reasoning (Oaksford 2015). A third possibility is that people use spatial representations and processes to solve the inference tasks. Such processes are implemented in areas of the parietal cortices (for a review see Husain and Nachev 2007), which were undisrupted by TMS in our experiment. They are more concrete than language-based and probabilistic theories assume, but more abstract than visual images. Therefore, they could proceed smoothly in the present experiment. Importantly, Ragni et al. (2016) could indeed show that TMS applied to the parietal cortices hinders participants' ability to solve relational inferences. The "space to reason theory" gives a detailed description of the cognitive processes based on spatial layout models (Knauff 2013). In short, the theory says that people represent the "state of affairs" described in the premises in a spatial mental model. The core assumption then is the conception of reasoning as a cognitive process, in which spatially organized mental models of the given premises are constructed, and then alternative models are sequentially generated and inspected. A conclusion is true if it holds in all models that agree with the premises (Knauff 2013, 2018). The present findings might agree with this account when we assume that people switch to a more abstract—and more effective—spatial reasoning strategy, if TMS disrupts their ability to construct visual images in V1.

We do not want to hide that we initially had an additional hypothesis, which was not supported by our present results. For reasons of clarity, we did not mention this hypothesis before, but we initially expected that visual mental images might impede reasoning performance. In particular, we expected the well-known *visual impedance effect* under Vertex stimulation as found in previous behavioral and brain-imaging experiments (Knauff and Johnson-Laird 2002; Knauff et al. 2003). The reason is that the Vertex stimulation served as a control condition and therefore, we expected to replicate the previous findings. Thus, the *visual impedance effect* should have been present in the control condition (Vertex) but then disappear under V1 stimulation. However, this

effect was not really visible in our data. With good will, we can interpret the numeric difference between the visual problems (30% errors) and all other problems (28.33% errors) in this direction. At least, this difference goes in the expected direction. However, the trend was not significant, even if we appreciate that $p = .05$ is an arbitrary cut off. This failure to replicate the *visual impedance effect* might have several reasons. It can be due to the small sample size, it might have to do with the specific experimental environment in a TMS experiment, it might have to do with the many still unclear effects of TM stimulation, or it might have to do with the fact that the *visual impedance effect* is subtle by nature. At present, we cannot answer this question but we will run further experiments to see whether the effect plays out under other experimental conditions (e.g., different point in time for the stimulation). Although this is a challenge for future research, one result of the present study is indisputable: reasoning performance was elevated when participants' ability to construct visual images was disrupted by TMS on V1. This is an interesting novel finding that challenges the classical view that visual mental imagery helps people to reason accurately.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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