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Uncertain relational reasoning in the parietal cortex

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ABSTRACT

The psychology of reasoning is currently transitioning from the study of deductive inferences under certainty to inferences that have degrees of uncertainty in both their premises and conclusions; however, only a few studies have explored the cortical basis of uncertain reasoning. Using transcranial magnetic stimulation (TMS), we show that areas in the right superior parietal lobe (rSPL) are necessary for solving spatial relational reasoning problems under conditions of uncertainty. Twenty-four participants had to decide whether a single presented order of objects agreed with a given set of indeterminate premises that could be interpreted in more than one way. During the presentation of the order, 10-Hz TMS was applied over the rSPL or a sham control site. Right SPL TMS during the inference phase disrupted performance in uncertain relational reasoning. Moreover, we found differences in the error rates between preferred mental models, alternative models, and inconsistent models. Our results suggest that different mechanisms are involved when people reason spatially and evaluate different kinds of uncertain conclusions.
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1. Introduction

Psychologists and cognitive neuroscientists have investigated human *deductive* reasoning for many years (reviewed in Goel, 2007; Knauff, 2007; Prado, Chadha, & Booth, 2011). An inference is deductively valid if the conclusion is *certainly* true, given that the premises are true. *Conditional reasoning* relies on if–then arguments, *categorical syllogisms* on quantifiers (such as all, some, or none), and *relational reasoning* on spatial, temporal, or other types of relational expressions. Psychologists found that some of these deductive inferences are simple for most people but the same people commit many logical errors in other reasoning tasks. People's logical errors are not random but instead show many systematic deviations from logical norms (e.g., Evans, 1989; Manktelow, 1999). Different cognitive theories explain these deviations from classical formal logic by means of mental inference rules, mental models, or probabilistic theories of reasoning (Johnson-Laird, 2006; Oaksford & Chater, 2007; Rips, 1994; Van der Henst, 2002).

Cognitive neuroscientists explored the neural basis of *deductive* reasoning primarily via functional brain-imaging techniques and patient studies; they identified a complex fronto-temporo-parietal network as the basis of logical reasoning (Goel, 2007; Knauff, 2009a, 2009b; Prado et al., 2011). The findings were again not random. They show that bilateral temporal and parietal brain areas are involved in conditional and syllogistic reasoning, whereas areas in the right parietal cortex are involved in relational inferences. Prefrontal brain areas are involved in executive functions and conflict resolution processes during reasoning (Goel et al., 2007; Knauff, 2009). Moreover, a lateralized frontal–temporal system processes inferences with familiar content, whereas abstract logical inferences are processed in the right parietal cortical areas (Goel & Dolan, 2003).

Recent progress in these fields has been significant, but criticism of the deductive paradigm has increased. A primary criticism is that deductive reasoning that focuses on truth-preserving inferences does not resemble how people often reason in their everyday lives. Reasoning in daily life is often *uncertain*. While reasoning we often do not know that a conclusion necessarily follows from what we know but rather that it is more or less likely, plausible, or believable. Psychologists have investigated such uncertain inferences but to a lesser extent than certain deductive reasoning (Johnson-Laird, 2006; Johnson-Laird, Girotto, & Legrenzi, 2004; Oaksford & Chater, 2007). Only a few cognitive neuroscientists have investigated the neural basis of uncertainty in reasoning (e.g., Goel, Stollstorff, Nakic, Knutson, & Grafman, 2009;

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Waechter, Goel, Raymont, Kruger, & Grafman, 2013); we describe these studies below.

Here, we focus on *uncertain relational reasoning*. From the following premises, can you determine the order of the pear and the mango with certainty?

The apple is to the left of the lemon.
The lemon is to the left of the pear.
The mango is to the left of the orange.
The lemon is to the left of the mango.

No, you cannot give a certain answer to this question because the premises are *indeterminate*. No matter what arrangement you imagine, you can always think of another possibility that is also consistent with the premises. In the example, two arrangements agree with the premises:

(1)	apple	lemon	pear	mango	orange
(2)	apple	lemon	mango	orange	pear

Each line denotes a possibility in which the premises hold true. However, it is impossible to know for certain which of the arrangements might be the real arrangement. Therefore, for such uncertain relational descriptions no deductively valid inference is possible (except that nothing follows for the arrangement between the pear and the mango). Whenever you choose one of the possibilities, your decision has a certain *degree of uncertainty*.

Previous cognitive experiments have shown that people deal with such uncertain spatial reasoning problems by considering just one of the possibilities and ignoring others. For instance, the majority of people would choose, for the two alternatives presented above, the order in the first line (1) and act as if possibility (2) does not exist (Jahn, Knauff, & Johnson-Laird, 2007; Rauh et al., 2005).

The *theory of preferred mental models (PMMs)* explains such preferences (Knauff, 2013; Ragni & Knauff, 2013). In this theory the preferred possibility (1) is the *preferred mental model (PMM)* and the other possibility (2) is the *alternative mental model (AMM; please refer to Table 1*). The study presented below had two goals: to explore the causal role of the right superior parietal cortex in reasoning in light of uncertain relational premises, and to determine whether these brain areas are differentially involved in the processing of *PMMs (1)*, *AMMs (2)*, and *inconsistent models (IMMs) (3, 4)*. IMMs are orders of objects that conflict with the given premises, for example:

(3)	orange	lemon	pear	mango	apple
(4)	apple	mango	pear	lemon	orange

This article begins with a summary of what is known about the cortical basis of human reasoning with relations, followed by a description of the theory of PMMs. The PMM is the mental model of uncertain premises that comes to the reasoner's mind first and guides the inference process as long as nothing contradicts it. Based on this theory, we predict that the human brain processes PMMs, AMMs, and IMMs differently. In the main body of this article, we describe the transcranial magnetic stimulation (TMS; e.g., Walsh & Pascual-Leone, 2003) experiment in which we temporarily hindered neural processing in the right superior parietal lobe (rSPL). We chose this area based on previous studies with patients and fMRI, as described below. In the discussion, we argue that PMMs play an important role in uncertain spatial reasoning and that the rSPL is causally relevant to these uncertain relational inferences.

Table 1
An indeterminate problem and the three types of models.

1. Premise	The apple is left of the lemon					
2. Premise	The lemon is left of the pear					
3. Premise	The mango is left of the orange					
4. Premise	The lemon is left of the mango					
Models	apple	lemon	pear	mango	orange	PMM
	apple	lemon	mango	orange	pear	AMM
	orange	lemon	pear	mango	apple	IMM
	apple	mango	pear	lemon	orange	IMM

1.1. Previous findings from patient studies, fMRI, TMS, and NIRS

In the following, we summarize results from (1) patient studies on relational reasoning under certainty, (2) brain-imaging studies on reasoning under certainty, (3) patient studies on relational reasoning under uncertainty, (4) brain-imaging studies on uncertain reasoning, and (5) TMS and near-infrared spectroscopy (NIRS) studies on human reasoning.

1.1.1. Patient studies of relational reasoning under certainty

In an early study, Caramazza, Gordon, Zurif, and DeLuca (1976) presented relational statements, such as "Mike is taller than George" to patients with right or left brain hemisphere lesions. After reading the statements, the patients had to answer either a congruent ("Who is taller?") or incongruent ("Who is shorter?") question. The left-hemispheric lesion patients were more impaired in the congruent problems and, in contrast, the right-hemispheric lesion patients were more impaired in the incongruent problems. Read (1981) reported similar results with "real" inference problems consisting of two relational premises and congruent and incongruent conclusions that were deductively valid or invalid. Goel et al. (2007) studied patients with lateralized focal lesions to the right and left prefrontal cortices (PFCs) and healthy controls. In their study, the authors used transitive relations, such as "A is to B and B is to C; how is A to C?" Such inferences can be either valid or invalid and determinate or indeterminate; for instance, premises such as A > B and B > C are determinate and the logically valid conclusion is A > C, whereas the conclusion C > A is inconsistent with the premises and thus deductively invalid. In contrast, indeterminate premises, such as A > B and A > C, do not provide enough information to construct a single model, and three models are possible: A > B > C, A > C > B, or A > (B = C). Goel and colleagues asked patients to determine the relationship between B and C. For these objects, no valid conclusion exists (except that nothing follows for the arrangement of B and C) because in the first model B > C holds, in the second model C > B holds, and in the third model B = C holds. Goel and colleagues showed that patients with left PFC lesions were impaired in inferences with determinate premises (i.e., certain) and patients with right PFC lesions were impaired in inferences with indeterminate premises (i.e., uncertain). These results indicate that the right PFC is involved in the processing of uncertain information and ambiguity, a result that is supported by other studies (e.g., Koscik & Tranel, 2012; Vartanian & Goel, 2005).

1.1.2. Brain-imaging studies on relational reasoning under certainty

Goel, Gold, Kapur, and Houle (1998) and Knauff, Mulack, Kassubek, Salih, and Greenlee (2002) reported the first brain-imaging studies on relational reasoning. Goel and Dolan (2001) addressed activity in visual association areas using sentences with spatial content that was either concrete (e.g., "The apples are in the

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