Plausibility and Visualizability in Relational Belief Revision

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Abstract

Belief revision is required when new facts are incompatible with existing beliefs. In the present experiment, participants changed their mind about the spatial and non-spatial relations between objects. The participants received information about relations, which were subsequently contradicted by irrefutable counterfacts. The task was to decide which of the initial relations to retain and which ones to give up. Previous experiments showed that these decisions are guided by the linguistic asymmetry between located (LO) and reference objects (RO). Reasoners have a strong preference to relocate the LO of the counterfactual relation. Our experiment explores whether this robust effect can be overwritten by the plausibility of revised beliefs; and how visualizability of problems affects revision. We found the LO-preference to be robust even when the resulting representation is implausible; and that revision is impeded when problems are easy to visualize. The results shed new light on relational belief revision in humans.

Keywords: Relational reasoning; Spatial reasoning; Belief revision; Mental models, Visual impedance

Relational Reasoning and the Revision of Beliefs

Imagine you involuntarily put on some weight over the Christmas holidays. That is why, for the next couple of months, in order to get rid of the additional pounds, you consider nutrition which is low in fat and calories. You know that pasta, buckwheat, potatoes, and fruits are all low in fat, and further that potatoes are higher in calories than buckwheat is, and that pasta provides more energy than potatoes and fruits. Your ability to rank these, and even more, different types of food according to the amount of energy they provide enables you to conclude that fruits are a good choice when you want to pursue your aim of weight loss. This little example demonstrates that *reasoning with relations* is essential in our daily life. In fact, it is ubiquitous and it plays a vital role in higher cognitive processing, for instance, in planning and categorizing (Halford, Wilson, & Phillips, 1998; 2010; Hummel & Holyoak, 2005).

Now, imagine you learn about avocado fruits that they contain high amounts of fat. You presumably integrate this fact with ease into your knowledge base, although it is not coherent with what you thought you knew about fruits (that they were low in fat). The process of integrating non-consistent pieces of information into already existing belief sets is referred to as *belief revision* (e.g. Gärdenfors, 1988; Elio & Pelletier, 1997; Wolf, Rieger, & Knauff, 2012). Reasoners usually revise their beliefs about the state of the world when confronted with contradicting evidence. Indeed, we frequently encounter new facts that do not cohere with our beliefs. When the source of a new piece of information is reliable and the fact itself somewhat indisputable, we might consider taking it into account. In case we do, it entails that we update knowledge bases and revise current sets of beliefs.

Frequently, there are multiple ways in which the revision could be performed, implicating different decisions about which beliefs to maintain and which ones to discard. Consider your belief that fruits are a good choice when you want to lose weight: do you maintain it in the face of the fact that avocados are high in fat; or will you discard at least avocados from the diet menu? Do you still think of avocados as fruits after all? It is clear that belief revision is often accompanied by uncertainty and ambiguity.

The current study relies on recent work done in the field of relational belief revision. A recent finding in studies that looked at belief revision about spatial relations is that the revision is based on the variation of spatial mental models (Bucher, Krumnack, Nejasmic, & Knauff, 2011; Krumnack, Bucher, Nejasmic, & Knauff, 2011; Bucher & Nejasmic, 2012; Knauff, Bucher, Krumnack, & Nejasmic, 2013). Often, there are multiple (logically equal) alternatives for variations that would all re-establish consistency. However, human reasoners hold strong preferences for specific alternatives. These preferences can rely on linguistic cues provided by relational statements. The experiment presented here was designed to investigate whether reasoners still rely on these cues during revision, even when the resulting object relations are implausible. Furthermore, we compared reasoners´ performance in problems that were easy to visualize and easy to spatially represent.

Preferences in Spatial Belief Revision

Our recent experimental studies have focused on the revision of object arrangements. Imagine a person has reason to think that the objects X, Y, and Z are arranged in this linear order. The spatial mental model that is constructed can be sketched as:

X – Y – Z

Let us assume the reasoner then learns from a reliable and trustworthy source that as an incontrovertible fact, “object Z is to the left of object X”. This fact is inconsistent with the

reasoner´s model. In order to take the fact into account and – at the same time – keep changes to the model as little as possible, the reasoner can vary the model in two different ways: the X can be relocated; the Z can be relocated. These two alternatives are comparable, from a logical point of view.

The finding of recent studies is that reasoners encounter this ambiguity with clear and robust preferences. Preferred model revisions of the type introduced here are guided by cues provided by the conflicting statements. Binary relations - such as "Z left of X" - feature a functional asymmetry between the two objects, well known as distinction of figure and ground, target and anchor, or (the terminology used in the present context) "located" (LO; the "Z" in "Z left of X") and "reference" object (RO; the "X" in "Z left of X"). The asymmetry of LO and RO specifies the location of the LO relative to the location of the RO (Miller & Johnson-Laird, 1976; Talmy, 1983; Landauer & Jackendorff, 1993). Reasoners tend to perceive the RO´s position as fixed and inflexible while the LO is considered to be more flexible and locatable.

The following example sketches a reasoner´s characteristic preference for the revision of a horizontal linear arrangement of the objects X, Y, and Z:

Arrangement: X – Y – Z
Counterfact: Z is left of X,
with Z as the LO of the counterfact and X as the RO

Revisions: (1) Z – X – Y
(2) Y – Z – X

The revised arrangement (1) results from the relocation of the counterfact´s LO relative to its RO and is usually the preferred revision. The logical equivalent but non-preferred alternative (2), results from the relocation of the RO relative to the LO. The LO-preference is a strong effect. Indeed, reasoners apply this principle in around 90% of the problems of the described type (Bucher et al., 2011; Krumnack, Bucher, Nejasmic et al., 2011; Bucher & Nejasmic, 2012; Knauff et al., 2013).

Note that abstract entities such as X, Y, and Z are neutral with regard to the position within an arrangement. The same applies for objects such as fruits (apple, mango, orange) and tools (hammer, drill, pliers). Indeed these were the objects used in the experiments so far.

Here, as a novelty, we manipulated two factors: the plausibility of revisions and the visualizability of the statements. We used spatial and non-spatial relations of objects "that make sense", e.g. "an elephant is bigger than a fly". The statements used in the problems differed with regard to their visualizability, i.e. in their extent to which they provoke picture-like representations ("mental images").

The first question is: do reasoners still apply the LO-principle when the revised model is implausible? In fact, reasoners often base their problem solutions on the plausibility of the content or on prior experiences within a certain field (Newstead, Pollard, Evans, & Allen, 1992; Klauer, Musch, & Naumer, 2000; Evans, 2008, DeNeys, 2006; Knauff, Budeck, Wolf, & Hamburger, 2010). These content effects show the strong tendency of reasoners to take into account what is meaningful or plausible. On the other hand, the LO-preference is a strong effect.

The second question is: does the visualizability of a problem modulate revision? Relations which are easy to visualize, impede reasoning (Knauff & Johnson-Laird, 2002; Knauff, Fangmeier, Ruff, & Johnson-Laird, 2003; Knauff & May, 2006; Knauff, 2009). Mental images are considered to be irrelevant for reasoning itself but the inspection of the images appears to slow down thinking and makes it more prone to errors. This so-called *visual impedance effect* occurs complementary to the facilitating effect of spatial relations (Knauff, 2009; Knauff, 2013). Spatial belief revision is conceived as the manipulation of spatial mental models. The assumption for the current experiment is that models which are easy to mentalize as visual images should accordingly be harder to manipulate by a reasoner than models constructed from easy to spatially representable statements.

In order to prepare the manipulation of the experimental problems´ visualizability, we conducted a pilot study.

Pilot study: the Visualizability of Statements

Participants of the pilot study rated statements with regard to their visualizability. This procedure allowed the allocation of statements to categories: visual, neutral, and spatial.

Method

30 volunteers (14 male; aged from 19 to 55) participated in the study. Each of them rated individually, 72 binary spatial and non-spatial relational statements according to their visualizability. The statements were accessible online via a link sent by email. They were generated and the data collected, using LimeSurvey, Version 1.92+ software. Example statements are: "Asparagus is thinner than cucumber"; "Cucumber is thinner than cabbage"; "Whisper is quieter than speech"; "Speech is quieter than scream".

Participants rated the subjectively perceived visualizability of each statement on a scale with the points: "very easy to visualize"; "easy to visualize"; "easy to visualize and spatially represent"; "easy to spatially represent"; very easy to spatially represent"; and "neither easy to visualize nor to spatially represent". The four most clear-cut rated statements from the three categories, "very easy to visualize", "neither easy to visualize nor to spatially represent", and "easy to spatially represent" were chosen as experimental material. In accordance with these ratings, the relations were allocated to one of three experimental conditions: "visual"; "neutral", "spatial". Table 1 shows example statements.

Table 1: Examples of statements used in the experiment

Visual
The cucumber is thinner than the pumpkin. The asparagus is thinner than the cucumber.
Neutral
The bird is weaker than the dog. The dog is weaker than the polar bear.
Spatial
Russia is further east than Poland. Poland is further east than Germany.

Discussion of the Pilot Study

It is clear that many people experience their thinking as inspection of visual images. However, our pilot study indicates that some relations are more "visual" than others. The results show that, on the one hand, the categories "visual", "neutral", and "spatial" have no clear-cut borders. On the other hand, however, the results also clearly show that some relations are experienced as more visual than others while some relations are experienced as more spatial than others. So, we do not have relations that are purely visual or spatial. However, for our main experiment we could identify relations which are more visual or more spatial than other relations.

Experiment: Plausibility and Visualizability

For the main experiment, the visualizabilty of the problems and the plausibility of revisions, were manipulated. Regarding plausibility, we relied on common knowledge. We assumed that a statement such as "the father is younger than the grandfather" is regarded as plausible, while the invers relation, "the grandfather is younger than the father" as implausible.

Method

Participants A new group of 20 volunteers (8 male; age range from 20 – 35; all native speakers of German) gave written informed consent to participation. They were tested individually in a quiet lab room.

Materials, Procedure, and Design The experiment is based on a 3 × 2 (within-subject) design. We manipulated the factors visualizability (visual, neutral, spatial) and plausibility (plausible, implausible). The experiment consisted of 64 problems in the visual, neutral, and spatial condition, respectively. During the revision phase, participants chose between plausible and implausible revised models.

In the first phase, the description phase, the participant received two statements (premises, P) describing the relations between three entities. In half of the problems, P1 was plausible and P2 implausible. In the other half, it was reversed. The premises were presented in a sequential manner, each at one time, by the participants´ own speed. See an example problem of the "visual" condition below:

Description:
P1: "Asparagus is thinner than cucumber"
P2: "Pumpkin is thinner than asparagus"

The task of the participants was to order the entities according to the description. Subsequently, two "models" were presented on the left and the right side of the monitor. One of the models was "correct", i.e. it was in agreement with P1 and P2, the other one was "incorrect".

Models constructed from the description:
Correct: Pumpkin Asparagus Cucumber
Incorrect: Cucumber Asparagus Pumpkin

Presentation locations of correct and incorrect models on the left and right side of the monitor were counterbalanced across the experiment. Participants were asked to indicate the correct model by pressing a left or right button. This step of the "correct model choice" was implemented in order to warrant that participants constructed the "correct model" before entering the next phase of a problem.

There is evidence that reasoners order objects spatially even when the relations are non-spatial. "Venus shines brighter than the moon but the sun shines even brighter", can easily be reflected by the order: Moon – Venus – Sun. Relations, also non-spatial ones, are thought to be closely linked to space. The argument of many researchers is that mental space is relational (rather than geometrical) space (e.g. Knauff, 1999; Knauff, 2013). This notion is corroborated by many findings, e.g. that spatial distance effects also occur with non-spatial relations (Prado, Van der Henst, & Noveck, 2008; Prado, Chadha, & Booth, 2011).

Indeed, participants´ performance was very accurate. In more than 90 % of the cases (M = 92.90 %; SD = 0.26), the correct models were selected. The few incorrect problems were excluded from further analysis.

In the second phase, the participants received a third premise which they were explicitly instructed to treat as an incontrovertible fact (while the instruction included the hint that the participant could not be entirely sure whether the description was true). The "fact" was always plausible. In half of the problems, it was consistent with P1 and P2; in the other half (see the example below) it was inconsistent.

Counterfact: "Cucumber is thinner than pumpkin"

The participants decided - using "yes"- and "no"-buttons - whether the fact was in agreement with the initial statements or not. Again, participants performed very accurate in this phase. In 86.20 % (SD = 10.59) of the problems, the participants decided correctly. Incorrect problems were eliminated from further analysis, so were the consistent ones.

The third phase, the revision, was the most interesting part of the experiment. This part followed only if the participant recognized a fact as inconsistent with the initial description. Participants were then instructed to revise their

assumption about the objects´ relations by taking into account the counterfact. Two alternative revised models, both variations of the initial model, taking into account the fact while preserving as much of the initial information as possible, were presented on the screen. The two revised models were presented on the left and the right side of the computer monitor. The task was to choose among the models the one which matched the participant´s assumption about the revised object relations. Choices were indicated by left and right button presses. One of the revised models was *plausible*; the other one was *implausible*. The question was whether reasoners still apply the LO-principle or whether they prefer revisions based on the plausibility. The two alternative revised models for the example above were:

(1) Cucumber Pumpkin Asparagus
(2) Asparagus Cucumber Pumpkin

Note that model (1) results from the relocation of the LO of the fact (which is the cucumber) but leads to an implausible order of objects. Model (2), in contrast, results from the relocation of the RO of the fact (which is the pumpkin) but leads to a plausible order of the objects. Over the entire set of problems, in half of the problems the LO-principle led to implausible and the RO-principle into plausible relations of the entities (as in the example above), in the other half of the problems it was reversed.

Revision choices and duration were recorded. The problems were presented in a random order. They were preceded by eight practice trials (not analyzed). All stimuli were generated, presented, and recorded with Superlab 4.0 (Cedrus Corporation, San Pedro, CA, 1999) with an RB-530 response box running on a standard personal computer connected to a 19''-monitor.

Results and Discussion

In the first analyses, we examined whether revision preferences were based on plausibility. Subsequently, we looked at the effects of visualizability. We also looked at the interactions between plausibility and visualizability. However, none of them reached the level of statistical significance (*p*s > .05).

Plausibility: ANOVAs were calculated, with the factors Plausibility (plausible, implausible) × Relocated Object (LO, RO), separately for the frequency (in percent) of the respective revision choices and revision duration (in seconds). Both ANOVAs revealed a main effect of Relocated Object (choices: [F (1,19) = 71.91; $p < .001$; η^2_{part} = .79]; duration: [F(1,19) = 6.53; p = .019; η^2_{part} = .26]; all other *p*s > .20). LOs were relocated more often and faster compared to ROs. Choices LO vs. RO: M = 78.77 %; SD = 14.99 vs. M = 21.23 %; SD = 14.99; t(19) = 8.59; $p < .001$; duration LO vs. RO: M = 2.69 s; SD = 1.71 vs. M = 3.46 s; SD = 1.74: t(19) = -2.35; p = .03).

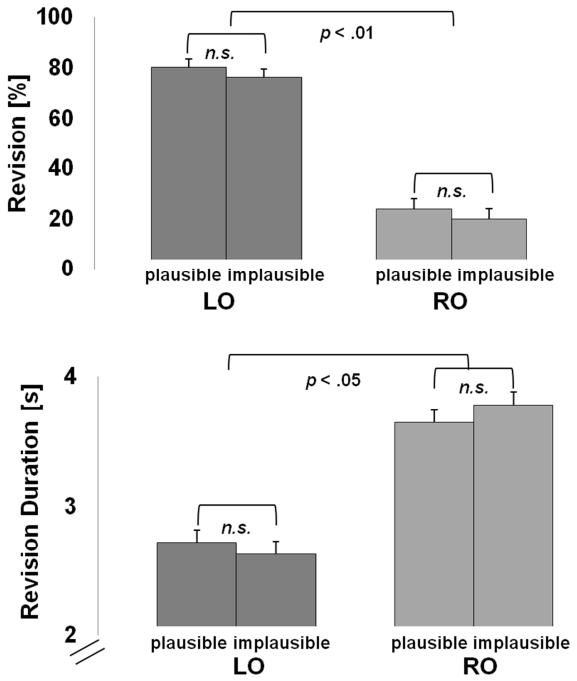

Figure 1. Revisions [%] and revision durations [s; error bars indicate standard errors] of "located" (LO) and "reference" objects (RO) showed an LO-effect. The preference was not modulated by plausibility

Figure 1 provides a graphically overview of the data. The result suggests that reasoners were guided by the distinction of LO and RO provided by the counterfactual relation. They followed the asymmetry of the objects and relied on the LO-principle. Plausibility did not overwrite this preference. Next, we examined the impact of the visualizability of the statements. The question was: does the easiness to construct a visual mental image or a spatial representation of the problems affect reasoning and belief revision?

Visualizability: in order to compare the revision duration of visual, neutral and spatial problems, an ANOVA with the within-subject factor Visualizability (visual, neutral, spatial) was calculated. It indicated a significant main effect [F(2,18) = 4.80; p = .014; η^2_{part} = 2.02]. When the statements were easy to visualize, the revision duration was significantly higher (M = 3.00s; SD = 1.3) compared to neutral and spatial problems (neutral: t(19) = -2.70; p = .014; spatial: t(19) = -2.73; p = .013). Revision duration for neutral (M = 2.60s; SD = 1.60) and spatial problems (M = 2.6s; SD = 1.3) were comparable (p > .85).

Figure 2 provides a graphical overview. The result clearly suggests an impeding effect of statements that are easy to visualize. We also looked at the interaction between visualizability and relocated object, which was non-significant (p > .35).

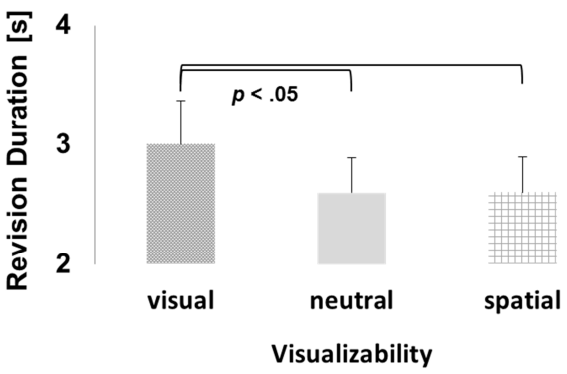

Figure 2. Mean revision durations of different relation types [s; error bars indicate standard errors] indicate a visual impedance effect

General Discussion

Belief revision is performed in order to re-establish consistency within belief sets (Gärdenfors, 1988). Frequently, there exists ambiguity because there are multiple solutions for revision. The present experiment on relational belief revision agrees with recent work suggesting that reasoners solve this ambiguity with strong preferences. Recent experiments used objects (e.g. fruits) which are "neutral" regarding their position within object arrangements. These objects were also not related to the individuals´ prior knowledge or pre-existing beliefs. (e.g. Knauff et al., 2013). The current experiment, in contrast, addressed two novel aspects in reasoning with spatial and non-spatial relations: the plausibility of a relation and the visualizability of the reasoning problems. Both aspects have been shown to affect reasoning in general (e.g. Evans, 2008; e.g. Knauff, 2009).

A powerful theory in cognitive science puts forward that reasoners represent situations and states of the world in *"mental models"*; and that these models provide the basis for reasoning (Johnson-Laird & Byrne, 1991; Goodwin & Johnson-Laird, 2005; Krumnack, Bucher, Nejasmic, Knauff, 2010; Krumnack, Bucher, Nejasmic; Nebel, & Knauff, 2011). Indeed, the mental model theory is corroborated by many phenomena. Moreover, model-based reasoning rather than the application of formal rules (e.g. Rips, 1994) nicely explains why reasoners often ignore the logical form of an argument. In fact, reasoners often base their problem solutions on the plausibility of the content or on prior experiences within a certain field, rather than on the validity of a conclusion (Newstead et al., 1992; Klauer et al., 2000; Evans, 2008, DeNeys, 2006; Knauff et al., 2010). These content effects show that reasoners have a strong tendency to take into account what is meaningful or plausible to them, even when this entails a trade-off with logic.

Recent findings on spatial belief revision suggest that reasoners vary spatial mental models and that they prefer certain variations above others. The variation of simple spatial models of "neutral" objects was found to be based on a principle which we call the LO-preference. The first aim of the current experiment was to test whether reasoners hold on to that preference, even when it leads to implausible models. Our data suggest that they do. The LO-preference remained the guiding revision principle even when the resulting model was implausible.

Are there alternative interpretations of this result? One alternative account is that the effect is due to the specific layout of our experiment. In fact, during the construction phase, reasoners were forced to partially "ignore" plausibility of relations in order to construct the correct initial model from plausible and implausible statements. This might have triggered them to do the same in the revision process. Thus, they also ignored the plausibility of the revised model. We think that this might be a possible explanation for the finding that the LO-preference was stronger than the plausibility of the revised model. However, we think that the robustness of the LO-preferences is still an important result. In our future research, we will explore whether the plausibility effect is more powerful in more complex revision tasks. We assume that with more complex problems, the LO-effect on model variation would disappear and "plausibility" would play a more important role.

An important finding in the area of relational reasoning is that the visualizablity of a relation can modulate reasoning performance. Relations which are easy to visualize as mental images impede reasoning (e.g. Knauff & Johnson-Laird, 2002). Reasoning with relations is best described by the construction and the manipulation of *spatial mental models* (e.g. Johnson-Laird & Byrne, 1991; Schaecken, Johnson-Laird, P. N., & d'Ydewalle, 1996; Goodwin & Johnson-Laird, 2005; Jahn, Knauff, & Johnson-Laird, 2007; Nejasmic, Krumnack, Bucher, & Knauff, 2011). It is likely that problems that are easy to spatially represent accommodate reasoning because of their shared nature with (spatial) mental models. Image-like representations, in contrast, impede reasoning because they hold additional but irrelevant information (Knauff, 2009; 2013). Our results corroborate these assumptions. With the present experiment, we found an influence of the visualizability on revision. Problems that were easy to visualize appeared to impede the revision process. Indeed, visual problems seem to provide an additional effort which slows down the revision process. In contrast, relations that were rated as easy to represent spatially were manipulated faster during the revision phase. This is in line with the assumption that those relations accommodate revision because they share their spatial structure with the spatial model that is varied. In our experiment, spatial and neutral relations were both processed faster than visual relations. This result supports the assumption that spatial and non-spatial relations are both easily integrated into spatial models. Pursuing this thought could possibly reveal more interesting aspects of the mental space as relational space (Knauff, 1999; Prado et al., 2008; Prado et al., 2011).

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References

Bucher, L., Krumnack, A., Nejasmic J., & Knauff, M. (2011). Cognitive processes underlying spatial belief revision. In L. Carlson, C. Hölscher, T. Shipley (Eds.), *Proceedings of the 33rd Annual Conference of the Cognitive Science Society* (pp. 3477-3482). Austin, TX: Cognitive Science Society.

Bucher, L. & Nejasmic, J. (2012). Relocating multiple objects during belief revision. In C. Stachniss, K. Schill, & D. Uttal (Eds.), *Lecture Notes in Artificial Intelligence: Spatial Cognition* (pp. 476-491). Berlin, Germany: Springer.

De Neys, W. (2006).Dual processing in reasoning - Two systems but one reasoner. *Psychological Science. 17,* 428-433.

Elio, R., & Pellitier, F. J. (1997). Belief change as propositional update. *Cognitive Science, 2,* 419-460.

Evans, J. St. B. T. (2008). Dual-processing accounts of reasoning, judgment, and social Cognition. *Annual Review of Psychology, 59,* 255–278.

Gärdenfors, P. (1988). *Knowledge in flux.* Cambridge, MA: MIT Press.

Goodwin, G. P., & Johnson-Laird, P. N. (2005).Reasoning with relations. *Psychological Review, 112,* 468-493.

Jahn, G., Knauff, M., & Johnson-Laird, P. N. (2007). Preferred mental models in reasoning about spatial relations. *Memory & Cognition, 35,* 2075-2087.

Johnson-Laird, P. N., & Byrne, R. M. J. (1991). *Deduction.* Erlbaum, Hove (1991).

Klauer, K. C., Musch, J., & Naumer, B. (2000). On belief bias in syllogistic reasoning. *Psychological Review, 107,* 852-84.

Knauff, M. (1999). The cognitive adequacy of Allen's interval calculus for qualitative spatial representation and reasoning. *Spatial Cognition and Computation, 1,* 261-290.

Knauff, M. (2009). A neuro-cognitive theory of deductive relational reasoning with mental models and visual images. *Spatial Cognition & Computation, 9,* 109-137.

Knauff, M. (2013). *Space to Reason.* Cambridge, MA: MIT Press.

Knauff, M., Bucher, L., Krumnack, A., & Nejasmic, J. (2013). Spatial belief revision. *Journal of Cognitive Psychology, 1,* 1-10.

Knauff, M., Budeck, C., Wolf, A. G., & Hamburger, K. (2010). The illogicality of stockbrokers: Psychological experiments on the effects of prior knowledge and belief biases on logical reasoning in stock trading. *PLoS One, 5(10), e13483. doi:10.1371/ journal.pone.0013483.*

Knauff, M., Fangmeier, T., Ruff, C. C., & Johnson-Laird, P. N. (2003). Reasoning, models, and images: Behavioral measures and cortical activity. *Journal of Cognitive Neuroscience, 15,* 559-573.

Knauff, M., & Johnson-Laird, P. N. (2002). Visual imagery can impede reasoning. *Memory & Cognition, 30,* 363-371.

Knauff, M., & May, E. (2006). Mental imagery, reasoning, and blindness. *Quarterly Journal of Experimental Psychology, 59,* 161–177.

Krumnack, A., Bucher, L., Nejasmic, J., & Knauff, M. (2010). Spatial reasoning as verbal reasoning. In S. Ohlsson & R. Catrambone (Eds.), *Proceedings of the 32nd Annual Conference of the Cognitive Science Society* (pp. 1002-1007). Austin, TX: Cognitive Science Society.

Krumnack, A., Bucher, L., Nejasmic, J., & Knauff, M. (2011). Efficiency and minimal change in spatial belief revision. In L. Carlson, C. Hölscher, & T. Shipley (Eds.), *Proceedings of the 33rd Annual Conference of the Cognitive Science Society* (pp. 2270-2275). Austin, TX: Cognitive Science Society.

Krumnack, A., Bucher, L., Nejasmic, J., Nebel, B., & Knauff, M. (2011). A model for relational reasoning as verbal reasoning. *Cognitive Systems Research, 11,* 377-392.

Landau, B. & Jackendoff, R. (1993) "What" and "where" in spatial language and spatial cognition. *Behavioral and Brain Sciences, 16,* 217–265.

Miller, G. A. & Johnson-Laird, P. N. (1976). *Language and Perception.* Cambridge MA: Havard University Press.

Nejasmic, J., Krumnack, A., Bucher, L., & Knauff, M. (2011). Cognitive processes underlying the continuity effect in spatial reasoning In L. Carlson, C. Holscher, & T. Shipley (Eds.), *Proceedings of the 33rd Annual Conference of the Cognitive Science Society* (pp. 1127-1132). Austin, TX: Cognitive Science Society.

Newstead, S. E., Pollard, P., Evans, J., & Allen, J. (1992). The source of belief bias in syllogistic reasoning. *Cognition, 45,* 257-284.

Prado, J., Chadha, A., & Booth, J. R. (2011). The brain network for deductive reasoning: a quantitative meta-analysis of 28 neuroimaging studies. *Journal of Cognitive Neuroscience, 23,* 3483-3497.

Prado, J., Van Der Henst, J.-B., & Noveck, I. (2008). Spatial associations in relational reasoning: Evidence for a SNARC-like effect. *The Quaterly Journal of Experimental Psychology, 61,* 1143 – 1150.

Rips, L. J. (1994). *The Psychology of Proof.* Cambridge, MA: MIT Press.

Schaecken, W., Johnson-Laird, P. N., & d'Ydewalle, G. (1996). Mental models and temporal reasoning. *Cognition, 60,* 205-234.

Talmy, L. (1983). How language structures space. In H. L. Pick & L. P. Acredolo (Eds.), *Spatial Orientation: Theory, Research and Application* (pp. 225-282). London, UK: Plenum.

Wolf, A.G., Rieger, S., & Knauff, M. (2012). The effects of source trustworthiness and inference type on human belief revision. *Thinking & Reasoning, 18,* 417-440