



COGNITIVE AND NEURONAL CORRELATES OF SPATIAL BELIEF REVISION

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Abstract

Humans frequently need to “change their minds” in the light of information that contradicts an existing set of beliefs. They have to decide which beliefs to retain and which ones to retract. The present thesis is concerned with the construction and revision of beliefs in the spatial context. Revision is assumed to be a variation process that is based on the relocation of objects within initially constructed spatial mental models. Usually, there are several alternatives for model variation that re-establish consistency within belief sets, and frequently, these alternatives are logically equivalent. Nevertheless, human reasoners show clear preferences for certain alternatives. The assumption is that preferences result from the application of principles that are cognitively more economic than others. The present thesis is concerned with determinants for economic strategies for belief construction and belief revision and provides an outlook how findings from spatial belief revision studies could be implemented in more practical, but related domains.

Zusammenfassung

Um aktiv mit der Umwelt agieren und auf neue, unvorhergesehene Gegebenheiten reagieren zu können, ist es notwendig, dass Menschen ihre Überzeugungen anpassen und verändern. Sie müssen in der Lage sein zu entscheiden, welche Informationen sie beibehalten und welche sie bereit sind im Lichte neuer, widersprüchlicher Informationen aufzugeben. Die vorliegende Dissertation beschäftigt sich mit der Frage wie Menschen Vorstellungen über die räumliche Anordnung von Objekten konstruieren und revidieren. In insgesamt fünf Kapiteln werden kognitive Verarbeitungsprozesse untersucht, die es Menschen ermöglichen Informationen mit räumlichem Inhalt zu verarbeiten, mental zu repräsentieren und zu manipulieren. In der Dissertation werden Befunde vorgestellt, die Aufschluss über die zugrundeliegenden kognitiven Prozesse sowie neuronalen Korrelate von Konstruktionen und Revisionen räumlicher Vorstellungen, geben. Menschen weisen in beiden Bereichen spezifische Präferenzen auf, die es ermöglichen ökonomische Prinzipien menschlicher Denkprozesse in einen übergeordneten Kontext zu bringen.

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Introduction

“I believe in God, the Father almighty, creator of heaven and earth. I believe in Jesus Christ, his only Son, our Lord” (Catechism of the Catholic Church, Chapter 3 Article 2, 1993). It is undisputed that humans tend to use the phrase “I believe” in different daily situations for example “I believe you are right”, “I believe it is unlikely that”, “I believe that Frankfurt is a city in Germany”, or even “I believe in God”. As well, different humans believe different things. But what do we believe in fact and how are our beliefs represented from a cognitive perspective of view? How do we create our beliefs and do we adhere to them in the exact same manner? Certainly not! Some of our beliefs are uncertain, and they are just believed until no plausible alternative exist. In the cases where alternatives occur, there is a need to adjust what we believe to be true. However, our beliefs are used to cope with every-day situations and on their basis, we are able to make conclusions. No matter if you have to solve a problem, try to describe a route, or reproduce the content of a story – mental capabilities are required and a special case of human reasoning is concerned with processing spatial information. In this context, reasoning means generating and manipulating beliefs concerning an object’s position on the basis of information about its spatial relation to other objects. For example, in way-finding we use prominent buildings such as church towers to navigate our way through an unknown part of a city and we represent mentally our route, actual circumstances, and general knowledge about the given situation (e.g. Winter, Tomko, Elias, & Sester, 2008). The present thesis is especially concerned with the construction and revision of beliefs during reasoning about spatial relations. From a theoretical and experimental point of view, different aspects for underlying cognitive processes were worked out and the following is intended to introduce three main pillars of the present thesis: spatial belief construction, linguistic aspects of spatial reasoning, and spatial belief revision.

Spatial belief construction

First of all, before we can even adjust beliefs, we need to create beliefs. For daily life, we use our beliefs to derive conclusions and to represent mentally what we know

about the world. Our reasoning capabilities are based on mental representations of given information that we had received beforehand. In psychological laboratories, reasoning with spatial relations is studied primarily with problems such as:

(1a) A is to the left of B.

(1b) B is to the left of C.

(1c) Is A to the left of C?

Sentences (1a) and (1b) are called “premises”, while the sentence (1c) that has to be checked for validity is usually referred to as “conclusion”. A problem can consist of any number of premises, although the most commonly studied form of this class of problems contains no more than two premises and one conclusion (thus often called “three-term-series problems”, e.g. Potts & Scholz, 1975). The spatial relations “left of” and “right of” establish transitivity, i.e. the relation between A and C can be deduced from the information about the relation of A to B and of B to C. Another set of relations is “next to”, “beside” etc. Such relations are non-transitive and typically describe the spatial relations between objects in a topological form (Knauff & Ragni, 2011; Jahn, Knauff, & Johnson-Laird, 2007).

In cognitive psychology, two major theoretical positions have emerged that describe how people reason about such problems. The rule-based theories are primarily represented by the work of Rips (1994), Braine and O’Brein (1998), and van der Henst (2002). These theories claim that reasoners rely on formal rules of inference akin to those of formal logic, and that inference is a process of proof in which the rules are applied to mental processes. The formal rules govern sentential connectives such as “if” and quantifiers such as “any”, and they can account for relational inferences when they are supplemented with axioms governing transitivity, such as: For any x, y, and z, if x is taller than y and y is taller than z, then x is taller than z. The rules are represented in the human mind and the sequence of applied rules results in a mental proof or derivation that is seen as analogous to the proofs of formal logic (Rips, 1994). However, this position has serious

difficulties to explain inferences with spatial relations (overviews in Goodwin & Johnson-Laird, 2005; Knauff, 2009, 2013).

For this reason the theoretical framework for the present thesis is mainly based on the mental models theory of human reasoning (Johnson-Laird, 2001; 2006; Johnson-Laird & Byrne, 1991) and the extension of the theory which is especially concerned with mental models in the spatial domain (Knauff, Rauh, & Schlieder, 1995; Knauff, Rauh, Schlieder, & Strube, 1998; Rauh, Hagen, Kuss, Knauff, Schlieder, & Strube, 2005; Jahn, et al., 2007; Ragni, Knauff, & Nebel, 2005). According to this theory, human reasoning with spatial relations relies on the construction of integrated mental representations of the information that is given in the reasoning problem's premises (Craik, 1943; Goodwin & Johnson-Laird, 2005; Johnson-Laird & Byrne, 1991; Johnson-Laird, 2001; Polk & Newell, 1995). The integrated representation is a model in the strict logical sense and it represents in a small and compressed way how "reality" could be – according to what is stated in the premises. Entities and relations that are found in the world are represented mentally by corresponding tokens and relations within a model, whereby a token is supposed to be a word or a symbol. Given the case that entities are named more than once in a spatial description, the information is incorporated and compressed – it is represented mentally just once by a token (Johnson-Laird, 1983; Johnson-Laird, 2001; Johnson-Laird & Byrne, 1991). In general, the model theory distinguishes between three different mental operations. For a better illustration, let us just start with an example: Imagine the following pairs of statements:

(2a) A says: "The cup is to the left of the glass."

(2b) B says: "The glass is to the left of the plate."

The mental model theory postulates that reasoners construct in the construction phase a mental model that reflects the information from the premises. For our example there is one layout that is consistent with this pair of statements:

(2c) cup glass plate

Once a model is constructed, reasoners can infer in the inspection phase pieces of information which were not explicitly given by the premises. From the layout (2c), the only valid conclusion is that the cup is to the left of the plate, or vice versa that the plate is to the right of the cup and that the glass is between the cup and the plate. Factors like an increasing number of spatial mental models or the continuity of the information that has to be integrated can impede the reasoning process (Ehrlich & Johnson-Laird, 1982; Evans, Newstead, & Byrne, 1993; Carreiras & Santamaria, 1997; Knauff et al., 1998; Boudreau & Pigeau, 2001). In the variation phase, individuals try to construct alternative models from the premises that refute the putative conclusion. If no such model is found, the putative conclusion is considered to be true (Johnson-Laird & Byrne, 1991). The difference between the classical model theory and the spatial version of the theory is that the model *validation* phase, is replaced by a model *variation* phase in which the search for alternative models is not random but implemented by an alteration process during which the alternative models are generated by the modification of the initial model. This process follows the “principle of minimal changes” and results in a specific order in which alternative models are considered (Knauff et al., 1995; Ragni et al., 2005; Rauh et al., 2005).

Vast empirical evidence suggests that the major strategy employed in reasoning with spatial relations is in fact based on the construction and inspection of spatial mental models (e.g. Boudreau & Pigeau, 2001; Carreiras & Santamaria, 1997; Knauff et al., 1995; Knauff et al., 1998; Maybery, Bain, & Halford, 1986; Schaeken, Girotto, & Johnson-Laird, 1998; Rauh, et al., 2005; Ragni et al., 2005; Schaeken & Johnson-Laird, 2000; Schaeken, Johnson-Laird & d’Ydewalle, 1996a, b; Vandierendonck & de Vooght, 1997).

Language comprehension in spatial reasoning

Polk and Newell (1995) pointed out that the model-based reasoning process as described above does not necessarily require deduction-specific, non-linguistic

mechanisms to operate on internal representations. Especially in cases when reasoners are not specifically trained on deductive reasoning, more general cognitive mechanisms might guide the reasoning process. The so called verbal reasoning approach assumes that cognitive processes in deductive reasoning are based upon the same processes as language comprehension and generation. Verbal reasoning describes reasoning as a transformation of verbal information provided by the premises of an inference problem. Verbal processes of encoding and re-encoding of a reasoning problem is performed on the basis of linguistic skills until the conclusion becomes obvious or until the reasoner gives up, especially when task-relevant information is provided verbally. Polk and Newell (1995) suggest that in such cases inferences follow immediately from the encoded information.

There is also evidence, that language comprehension is related to spatial representations (Rinck & Bower, 2004) and additionally, different theories of language assume a close connection between conceptual representations and a simulation-based language understanding (Bergen & Chan, 2005). Reading a word that represents a specific action for instance, appears to be sufficient to elicit activation of the motoric system of the brain (Pulvermüller, 2005). Glenberg and Kaschak (2002) report an action-sentence compatibility effect and support the notion that language understanding includes a bodily action. They asked participants to make judgments on sentences that describe actions towards the body (e.g., “Mark dealt the cards to you”) or away from the body (e.g., “You dealt the cards to Mark”). They were asked to make a response that required moving towards or away from their own bodies. Response times were faster when the response requires an arm movement in the same direction as the action described by the sentence. In this context, they proposed the indexical hypothesis, which assumes that language (e.g. words and phrases) becomes meaningful through grounded action. To describe language understanding, three processes are postulated. In the first phase ("indexing") the content of the language is established. In the second phase ("derivation of affordances") possibilities of interactions with things in an environment are derived. These affordances include not only the interaction but also the intention and goals a person has in that moment. The third phase ("meshing") describes a combination of previously derived affordances into feasible

actions to accomplish a goal. It is assumed that these processes interact dynamically and are used to establish a mental model (Glenberg & Robertson, 1999; Kaschak & Glenberg, 2000). Due to the fact that humans, in daily life, as a rule deal physically and mentally with objects characterized by different properties, it is conceivable that in this case reasoning processes differ from processes based on abstract symbols. Referring back to the introductory examples, this assumption implies that reasoning on the basis of sentence 1a and 1b with abstract symbols (A, B, and C) should differ from a cognitive perspective of view from reasoning on the basis of sentence 2a and 2b. In the second case humans would include experiences they have with named objects and they would take their intention in a particular situation into account, during reasoning.

Additionally, for the special case of verbatim spatial descriptions expressed in a binary relation with $r(X, Y)$, an asymmetric role of the two arguments is suggested. A binary relation holds semantic cues that result from the semantic distinction of X as the “to-be-located or located object” (LO) in contrast to Y as the “reference object” (RO). The asymmetry is determined by the temporal and spatial location of both arguments during reasoning processing. The RO appears as a fixed landmark whose location is known whereby the LO can be found relative to the known location of the RO (Miller & Johnson-Laird, 1976; Talmy, 1983; Landau & Jackendoff, 1993; Tenbrink, Andonova, & Coventry, 2011). In this sense the LO-RO asymmetry plays a crucial role for the construction of spatial mental models. For instance, in the first premise (1a “A is to the left of B”) the “A” is the LO and the “B” is the RO and it has been shown, that during the construction process the LO as the more flexible object is integrated into the mental model relative to the position of the RO (Oberauer & Wilhelm, 2000; Hörnig, Oberauer, & Weidenfeld, 2005; Oberauer, Hörnig, Weidenfeld, & Wilhelm, 2005). Logan (1994, 1995) proposes that attention is turned to a certain region by linguistic cues provided by these relations. Attention moves from a statement’s RO to the region the LO can be expected. The findings converge to that effect that reasoners consider an RO’s position as fixed while the LO is flexible and locatable relative to the RO’s position.

Spatial belief revision

In general, belief change is defined as a process in which a rational agent makes the transition from one belief state to another. In general it is assumed that the confrontation with new, inconsistent information regarding the actual belief state can be deemed as the starting point for subsequent belief changing processes (Elio & Pelletier, 1997). Elio and Pelletier (1994) distinguish between two different cases of belief change –belief update and belief revision. A belief update is performed when new information does not result into inconsistencies at all. In this case it is possible to add it to the current beliefs requiring belief modifications as less as possible. In contrast, a belief revision is performed in cases when new information differs seriously from actual beliefs. If a new piece of information is incompatible, and at the same time indisputable, there is a need to revise what has heretofore believed to be true. It is assumed that belief revision as a deliberate act is driven by something, and that this driving force includes the detection of a conflict within the belief state. This procedure is associated with a decision to accept the new information and to eliminate certain old beliefs. In the course of belief revision it has to be decided which beliefs to retain and which ones to retract in order to regain consistency within all given information at a moment (Elio & Pelletier, 1997).

In cognitive psychology, some work on belief revision and the effects of inconsistent propositions has been done outside the spatial domain. Reasoning with inconsistent conditional statements (“if ..., then...”) has been explored by Johnson-Laird, Girotto, and Legrenzi (2004). The authors showed that individuals try to construct a single mental model of a set of propositions, and infer that the set is inconsistent if the task is impossible. Another study has been done by Johnson-Laird, Legrenzi, and Girotto, and Legrenzi (2004). They report two studies with sets of inconsistent conditional assertions. The results show that as the number of possibilities compatible with the assertions increases, the difficulty of the task increases, and that individuals represent only what is true and not what is false according to assertions. This procedure avoids overloading memory, but it yields illusions of consistency although the set of assertions is inconsistent (Johnson-Laird et al., 2000).

A second problem arises if individuals have to revise their earlier assumptions to resolve the detected inconsistencies. There is also some experimental work on this issue that has been done outside the area of spatial reasoning. These studies primarily focus on questions concerning the form of the statements, their universality, and their believability. An influential study by Revlis, Lipkin, and Hayes (1971), for instance, showed that if a fact conflicted with the consequence of a general principle and a particular assertion, participants tended to reject the particular assertion (Revlis et al., 1971). Elio and Pelletier (1997) have examined links between the form and believability of statements. They suggested that conditional statements may be less believable than categorical statements. Politzer and Carles (2001) argued that any statement containing a sentential connective (“and”, “or”) may be less believable than a categorical statement. The authors assumed that doubt about a disjunction simply “stems from the rather trivial fact that it is more complex in that it contains a connection and has more chances to be the source of error” (Politzer & Carles, 2001, p. 224).

Other experiments examined the effects of the order of events on beliefs (e.g. Hogarth & Einhorn, 1992; Zhang, Johnson, & Wang, 1997). An especially interesting study has been done by Hasson and Johnson-Laird (2003). The authors were able to show that the entrenchment of beliefs fails to account for the fact that participants may abandon the proposition they rated as more believable (Hasson & Johnson-Laird, 2003). In addition, whether we assess a source to be reliable or not has an influence on the way we revise beliefs. If information is stated by a highly trustworthy source we are more inclined to adhere to a belief (Wolf, Rieger, & Knauff, 2012). However, the revision of spatial beliefs has not been explored so far and it is not clear which mental processes underlie the revision of beliefs about the spatial layouts of objects. Coming back to our introductory example (Sentence 2a and 2b) with the spatial arrangement of the three named objects:

(2c) cup glass plate

Imagine you receive additional information (which you know is correct and absolutely undisputed):

(2d) C says: “The cup is to the right of the plate.”

Actually, there is no layout that is consistent with all the propositions. One of the statements from A or B must be wrong! Whom do you believe more – A or B? Which statement is more believable? Which one are you inclined to reject and which one will you keep? Does it matter in what way we received the initial spatial information and do we consider general knowledge and experiences we have about and with named objects for spatial belief revision? What are neuronal correlates of underlying spatial belief revision capabilities? The present thesis intends to answer some of these questions.

Outline of the thesis

Based on cognitive processes underlying the construction of spatial beliefs and the role of language comprehension in reasoning with spatial content, the present work goes a step further and combines them with the focus on spatial belief revision. In the following part of the thesis 11 experimental studies are presented in four chapters, trying to give an answer to some of the previously presented questions.

In the first part, a study is presented that offers a new view on the understanding how reasoners construct mental models (*Chapter 1: The construction of spatial mental models- a new view on the continuity effect*). The study is concerned with the question how spatial information that is not directly related to each other is mentally processed. Four experiments were conducted to investigate the assumptions whether (1) reasoners construct more than one (preliminary) model and integrate the models afterwards, or alternatively (2) construct one preliminary model that is later modified. The results support the assumption that humans tend to use more efficient strategies during the construction of spatial mental models and reasoning (Halford et al., 2007).

The second part of the thesis goes a step further and investigates in three studies cognitive processes underlying spatial belief revision. More precisely, the question how humans revise initially constructed mental models in the face of uncertainty, becomes of particular importance. In order to take contradicting and at the same time incontrovertible facts into account and to re-establish consistency within a certain belief set, it is required that beliefs about the relations of objects in space have to be revised. Because up to now this research area was unexplored, a series of experiments has been conducted, investigating basic principles of spatial belief revision. Chapter 2- 4 (*Chapter 2: Cognitive processes underlying spatial belief revision; Chapter 3: Spatial belief revision; Chapter 4: Relocating multiple objects during belief revision*) introduce a spatial belief revision paradigm and form the basis for other studies presented in this thesis. On the basis of the theoretical framework of mental models the experiments were conducted investigating whether revision processes of initially constructed models are guided by vital steps remembered from the construction phase or whether they solely rely on spatial information provided by inconsistent facts. In the second case it is hypothesized that spatial belief revision processes are affected by the functional asymmetry between reference objects (RO) and the located objects (LO) of spatial relations. Evidence is reported for a clear revision preference that is basically guided by the asymmetry between a RO and an LO of a binary relation, even if revision according to a LO-principle implies a relocation of an additional object.

The third part of the thesis (*Chapter 5: Construction and Revision of Spatial Mental Models under High Task Demand*) builds a bridge between experimental findings of part one and part two. Two experiments follow the question whether spatial belief revision strategies differ when less cognitive resources are available for revision processes. To investigate this question, levels of difficulty of the construction processes of mental models were manipulated by the use of different premise orders. The study offers a new view on the understanding of spatial belief revision processes showing that increased difficulty of the construction of spatial models leads to a higher demand of cognitive resources which in turn modulates operations performed during the subsequent reasoning phase of revision.

The fourth part of the thesis uses the spatial belief revision paradigm that is introduced in chapter 2-4 and investigates whether spatial belief revision can be deemed as a mental relocation of objects within a mental model. For this reason, in Chapter 6 (*Chapter 6: Grounded Spatial Belief Revision*) the idea that human reasoning and language processing is not separate from experiences humans have with certain objects is transferred to the area of spatial belief revision. In three experiments participants were confronted with spatial descriptions consisting of objects with different physical properties (size, movability, and weight) in order to test whether imagined physical object properties influence which object is relocated within a mental model and which remains at its initial position. Results support findings concerning spatial belief revision strategies. They are mainly guided by the functional asymmetry between the LO and the RO of the inconsistent fact, but they also support the assumptions claimed out by theories concerning grounded cognition (e.g. Barsalou, 2008). Object properties influence the way humans revise their beliefs with spatial content, although different object properties are not considered in the same manner. Chapter 7 (*Chapter 7: Neuronal correlates of spatial belief revision*) presents an fMRI-study investigating neuronal correlates of spatial belief revision with the aim to get a deeper understanding of underlying cognitive processes. The spatial belief revision paradigm was slightly adapted for the fMRI study and results support the assumption that spatial belief revision relies on the variation of mental models, or more precisely, on the relocation of objects within a mental model.

The last experimental part of the thesis offers a wider view and new implications of spatial belief revision and relational reasoning. In four studies (*Chapter 8: Plausibility and visualizability in relational belief revision; Chapter 9: Spatial reasoning in native speakers of Russian and German; Chapter 10: Belief Revision and Way-finding; Chapter 11: A model for relational reasoning as verbal reasoning*) the basic cognitive principles suggested for spatial belief revision were connected with more general topics of spatial reasoning. Whereas in chapter 8 the influence of plausible spatial relations on belief revision principles was investigated, chapter 9 is concerned with spatial relational reasoning and the influence of language and culture. Spatial belief revision problems were

presented to native speakers of Russian and German. The study supports the assumption that the way how we process spatial descriptions has an influence on the construction and revision of spatial mental models. Chapter 10 (*Chapter 10: Belief Revision and Way-finding*) provides an outlook how findings from spatial belief revision studies could be implemented in a more practical, but related domain – way-finding. The last Chapter (*Chapter 11: A model for relational reasoning as verbal reasoning*) introduces an approach how relational reasoning can be conceived as verbal reasoning and provides algorithms for a computational implementation of the underlying construction and reasoning processes.

Please note, every subchapter is written as a single scientific study, so it is possible to read them completely separated from the other studies. At the same time this also means that for those who read the whole work some information might be repetitive, especially in the respective introductory sections of the studies. Additionally, in the conclusion at the end of the thesis all findings are briefly summarized, because they are more detailed discussed in every subchapter.

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Part 1

Chapter 1

The construction of spatial mental models

—

a new view on the continuity effect¹

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Abstract

Many studies show that spatial reasoning with information that describe relations between two or more objects relies on the construction and inspection of mental models. This article mainly focuses on the phenomenon that humans have more difficulties in processing spatial information that is not directly related to each other – for example, presented discontinuously – what is also known as the continuity effect. The article investigates how humans integrate such information into one unified mental model. In four experiments, we investigated the question whether (a) reasoners construct more than one (preliminary) model, with the first two premises presented in a discontinuous description, and integrate the models afterwards, or alternatively (b) construct one preliminary model that is later modified in the light of the last parts of problem description. The results support the second assumption and offer a new view on the continuity effect and the fundamental principles of model construction and variation in human spatial reasoning.

Introduction

In almost all everyday situations we are confronted with problems requiring mental capabilities to process spatial information. No matter if you are reading a map, describing a route, or planning to rearrange your furniture, you have to make your decisions on the basis of actual circumstances or general knowledge. Indeed, relational and spatial relational reasoning, required for solving the following reasoning problem, provides a crucial basis for complex thinking (Halford, Wilson, & Phillips, 1998, 2010): The current study focuses on the construction of spatial mental models (M) that result from verbal premises (P) of the following kind:

- P1. The apple is to the left of the peach. M1: apple–peach
- P2. The peach is to the left of the kiwi. M2: apple–peach–kiwi
- P3. The kiwi is to the left of the mango. M3: apple–peach–kiwi–mango

The mental model theory provides an explanation of how reasoners use the meaning of assertions and general knowledge to construct models that reflect the given information (Craik, 1943; Johnson-Laird & Byrne, 1991; Polk & Newell, 1995; Johnson-Laird, 2001; Goodwin & Johnson-Laird, 2005). In other words, it is assumed that people construct an integrated representation by translating given verbal descriptions into models (Craik, 1943). Entities and relations how they appear in the world are represented by corresponding tokens and relations within a mental model. A token is supposed to be a word or a symbol, and in cases where entities are named more than once in a spatial description, the respective information is incorporated and compressed in the way that the token is represented just once (Johnson-Laird, 1983, 2001; Johnson-Laird & Byrne, 1991).

In the example above, the linear orders of the objects M1–M3 result from the statements, also called premises P1–P3. From P1, M1 results. P2 informs about the relation between an object already represented in the model (peach) and a “new” object (kiwi). Accordingly, M1 is extended to become M2. Finally, M2 is completed to become M3, by the integration of the last object (mango) into the model according to the last premise of the current description, P3. The final result is one unified model (M3) that represents distances and relations between mental tokens corresponding to the real order of the named entities (Johnson-Laird, 1983; Johnson-Laird & Byrne, 1991; Knauff, Rauh, & Schlieder 1995; Vandierendonck & de Vooght, 1997; Knauff, Rauh, Schlieder, & Strube, 1998; Schaeken, Girotto, & Johnson-Laird, 1998; Goodwin & Johnson-Laird, 2005; Ragni, Knauff, & Nebel, 2005; Rauh, Hagen, Kuss, Knauff, Schlieder, & Strube, 2005).

With relational problems, the crucial role is played by relational complexity (Halford et al., 1998; Phillips & Niki, 2002). Relational complexity results from interactions of components such as the number of objects, relations, and the type of relation (binary, ternary, quaternary, and so on). Complexity draws on processing capacity – that is, the more complex a problem is, the more cognitive resources are required to solve it. It is easier to construct a mental model that represents two or three, than four or five objects (Byrne & Johnson-Laird, 1989; Carreiras & Santamaría, 1997; Halford et al., 1998; Goodwin & Johnson-Laird, 2005). Additionally, in a left–right dimension, humans prefer

to construct mental models with a starting point on the left and a working direction to the right, presumably to accommodate some sort of “cultural bias” (De Soto, London, & Handel, 1965; Huttenlocher, 1968; Chan & Bergen, 2005; Hörnig, Oberauer, & Weidenfeld, 2006; Spalek & Hammad, 2005; Krumnack, Bucher, Nejasmic, & Knauff, 2010; Krumnack, Bucher, Nejasmic; Nebel, & Knauff, 2011). A detailed computational model of spatial reasoning with mental models has been developed by Ragni and Knauff (2013).

A major challenge in reasoning with mental models occurs when relevant pieces of information are missing or available only at a later point in time during the reasoning process. The delayed availability of relevant bits of information often results in uncertainties and ambiguities rendering relational reasoning problems difficult. Imagine, for example, the following scenario: You are a new employee in a department, and your colleague Tom tells you:

- (1) “My office is to the left of Leo’s office”
- (2) “And Peter’s office is to the left of Bill’s office”

The description does not allow determining with certainty how the four offices are related to each other. Nonetheless, you will probably mentally arrange the offices, and most likely you will arrange them in the following order (successively integrating the terms in a left-to-right direction):

(M preliminary) Tom’s office – Leo’s office & Peter’s office – Bill’s office

It is only later that you find out that

- (3) “Bill’s office is to the left of Tom’s office”

Only the last premise allows you to mentally (re)arrange the offices in the correct order:

(M) Peter's office – Bill's office – Tom's office – Leo's office

To handle problems of this kind, it is essential to store preliminary or ambiguous information in memory. And there is evidence that humans construct just a single model, even if descriptions are ambiguous and allow the construction of more than one model. Only in some cases, in the second step, do reasoners try to vary the initial model in the light of complementing pieces of information, like in our office example (Knauff et al., 1995; Rauh, Schlieder, & Knauff, 1997; Ragni et al., 2005; Rauh et al., 2005; Ragni, Fangmeier, Webber, & Knauff, 2006; Krumnack et al., 2011). Such model variation processes are computationally reconstructed in the model of “*preferred inferences in reasoning with spatial mental models*” (PRISM; Ragni & Knauff, 2013).

The role of the premise order in construction tasks

Studies examining the construction and variation of mental models often use descriptions resembling our examples above (Huttenlocher, 1968; Clark, 1969; Haviland & Clark, 1974; Ehrlich & Johnson-Laird, 1982; Grosz, Joshi, & Weinstein, 1995; Baguley & Payne, 2000; Oberauer & Wilhelm, 2000; Oberauer, Hörnig, Weidenfeld, & Wilhelm, 2005). The descriptions are presented as *n-term series problems*, usually describing the relations of at least four objects (*terms*). Accordingly, a four-term series problem (4ts-problem) encompasses three relational premises: (1) Ar_1B , (2) Br_2C , and (3) Cr_3D with the terms A, B, C, and D representing objects and r_n (e.g. “left of”) the relation between these objects. The task is to find a valid conclusion, e.g. “A is left of D” (Johnson-Laird, 1972; Potts & Scholz, 1975; Knauff et al., 1998). The time participants need to come up with a valid conclusion (or to verify a given conclusion) is measured. The crucial point in these experimental settings is the manipulation of the order in which the premises are presented. The orders vary from “continuous”, “semi-continuous” to “discontinuous”:

continuous: Ar_1B , Br_2C , Cr_3D (like in the introductory example)

semi-continuous: Br_2C , Cr_3D , Ar_1B

discontinuous: Cr_3D , Ar_1B , Br_2C (resembling the office example)

A continuous premise order allows the successive straightforward integration of all objects into a model. The term “successive” here means that a “new” object introduced by the second and all subsequent premises is always related to an object that had already been integrated into the model before. After the basis of the model (A–B) is established according to the first premise, the model is constructed along one working direction – that is, further objects are attached to the rightmost position when working from left to right in the horizontal dimension, and to the leftmost position when working from right to left. A semi-continuous premise order allows the successive integration of the objects just as it is the case for continuous descriptions; however, the working direction changes during the course of the construction process. In cases where the model was constructed from left to right, the last object needs to be integrated to the leftmost position. Finally, a discontinuous premise order does not allow for the successive integration of objects. “New” objects introduced by a second premise have not been introduced by the preceding premise, such that it is not unambiguously clear for the reasoner how to continue the construction of the model after the first premise. It is only later that the order of the objects in the model becomes determinate by the third premise. Not surprisingly, findings show that it is easier (i.e., faster and less error-prone) to construct models with premises presented in continuous or semi-continuous than in discontinuous orders. The effect is known as “continuity effect” (Potts, 1972; Smith & Foos, 1975; Foos, Smith, Sabol, & Mynatt, 1976; Ehrlich & Johnson-Laird, 1982; Garnham, Oakhill & Johnson-Laird, 1982; Evans, Newstead, & Byrne, 1993; Rauh et al., 1997; Knauff et al., 1998; Knauff, 2006; Knauff, 2013)

While many studies have proved the existence of the *continuity effect*, it is not clear what causes the effect. One possibility is that people when working on a discontinuous problem try to construct just one integrated representation of both premises, but stop trying

the moment they become aware of the discontinuity (Oakhill & Johnson-Laird, 1984). Lacking an integrated model, reasoners are forced to keep premise information in either the original verbal format or an abstract form – for example, some sort of propositional format (Kintsch, 1974; Fodor, Fodor, & Garrett, 1975). Another explanation for the continuity effect is that reasoners construct two mental models that are held separately in memory. In this case, each of the models represents the two objects named in the first and in the second premise, respectively, and is integrated into one unified model as soon as the third premise reveals the missing link (Ehrlich & Johnson-Laird, 1982; Knauff et al., 1998). This and the previous account have in common that there is no integrated model of the information given by the premises and that later processing steps require additional cognitive effort (Maybery, Bain, & Halford, 1986; Klauer, Stegmaier, & Meiser, 1997; Rauh et al., 1997; Vandierendonck & de Vooght, 1997). Moreover, holding the first two premises in working memory is cognitively “uncomfortable” and bears a great risk of forgetting.

These are the two classical explanations for the continuity effect. However, there is a third alternative, which has not been considered in the literature, yet. The starting point is that the notion of “two separate models” that are temporary held in memory is contradicted by the assumption that humans prefer parsimonious cognitive strategies (Halford et al., 1998; Vandierendonck, Dierckx, & De Vooght, 2004; Schaeken, van der Henst, & Schroyend, 2007). Moreover, several studies show that people construct a single, typical model even if the premises allow for multiple possible models. This single model is the easiest to construct in working memory and can be varied in further steps of the inference. This initial model is often called *the preferred mental model* (Knauff, et al. 1995; Rauh et al., 1997; Knauff, et al. 1998; Goodwin & Johnson-Laird, 2005; Ragni & Knauff, 2013) and realizes the principle of mental models parsimony (Goodwin & Johnson-Laird, 2005). Based on these findings, it is reasonable to assume that preferred mental models also play a crucial role when people are confronted with problems in discontinuous premise orders. In such cases, people may actually start to construct an initial model, the preferred one, from the onset on and vary this model if the third premise is not consistent with this preferred model. So, there is no need to keep two separate

models in working memory, and the reasoner has to handle only one model, which is the preferred one.

Characteristics of such a preferred mental model have been algorithmically reconstructed in Ragni and Knauff (2013). In principle, the reasoner (a) seeks to integrate all tokens into the model as soon as possible, and (b) tries to avoid relocating objects that are already represented in the model. In other words, all objects are integrated into the model at the first free position that is not already occupied by another object and fulfils the spatial relation from the premise at hand (Knauff et al., 1995; Rauh et al., 1997; Ragni et al., 2005; Rauh et al., 2005; Ragni et al., 2006; Krumnack et al., 2011). Moreover, the preferences result from people's tendency to construct models from left to right (De Soto et al., 1965; Huttenlocher, 1968; Chan & Bergen, 2005; Spalek & Hammad, 2005; Hörnig et al., 2006) and to insert new entities to the endpoint on the rightmost side than to place new entities between already represented entities within a mental model (Krumnack et al., 2010, 2011). Additionally, humans try to counteract the more difficult task to represent a greater number of entities in a mental model by chunking entities within a mental representation (Halford et al., 1998; Vandierendonck et al., 2004; Schaeken et al., 2007). In the present study, we investigate different assumptions regarding the continuity effect and contrast the following two basic assumptions:

1. Hypothesis: Reasoners construct *more than one* (preliminary) model to represent the first two premises presented in a discontinuous description and integrate the models only later into a unified representation, with the third premise of the description. The continuity effect relies on the additional cognitive effort and time needed to integrate the separate models into a unified model with discontinuous descriptions as compared to continuous and semi-continuous descriptions that allow the successive construction of a single model.

2. Hypothesis: *One* preliminary model is constructed, regardless of the degree of continuity of the premise orders. However, preliminary models based on the non-determined first part of a discontinuous description (as opposed to a determined continuous description) frequently have to be altered in the light of the last part of the description. This modification process, which occurs with the construction of models in a discontinuous but not with continuous description, is what we suggest to be responsible for the continuity effect.

The present paper presents four experiments. All four experiments describe linear arrangements on the basis of premise orders, varying in the degree of continuity. The first experiment introduces the continuous, semi-continuous, and discontinuous premise orders, with the continuous and semi-continuous problems requiring a working direction from left to right. We expected to replicate the continuity effect with experiment1 (e.g., Ehrlich & Johnson-Laird, 1982; Knauff et al., 1998). Experiments 2-4 were designed to precisely contrast the two hypotheses. To that end, experiments 3 and 4 introduce an additional type of description, based on “quasi-discontinuous” premise orders. The experiments are described in more detail at a later time. Table 1 provides an overview of the premise orders used in the experiments.

Table 1
The premise orders introduced in the experiments

| | Premise order | | | |
|-------------|---------------|---------------------|-------------------------|---------------|
| | continuous | semi- continuous | quasi- discontinuous | discontinuous |
| Experiments | 1, 2 | 1, 2 | 3, 4 | 1, 2, 3, 4 |
| Premise 1 | $A r_1 B$ | $B r_2 C$ | $C r_3 D$ | $C r_3 D$ |
| Premise 2 | $B r_2 C$ | $C r_3 D$ | $A r_1 B$ | $A r_1 B$ |
| Premise 3 | $C r_3 D$ | $A r_1 B$ | $D r_2 A$ | $B r_2 C$ |

Experiment 1

Method

Participants. Twenty-five students from the University of Giessen (4 male; age: $M = 22.2$; $SD = 2.7$) were tested individually. They gave written informed consent and were

paid at a rate of 8€/hour for their participation. Data from five participants were excluded from the analysis due an extreme number of errors (more than 98%; $n = 2$) and extremely long reading times (> 6 s/first premises and more than 50% errors, $n = 3$). The experiment took approximately 45 min.

Materials, design, and procedure. Each participant solved 72 determinate 4ts-problems. Four practice trials (not analyzed) preceded the experimental trials. Participants received all instructions on the computer screen. The structure of the tasks was as follows: three premises were presented sequentially (in a self-paced manner and only one premise visible at one point in time) and randomly in three premise orders (continuous, semi-continuous, or discontinuous). They described the spatial relation between four small, equal-sized, and disyllabic objects (tools, fruits, or vegetables), using the relation “left of”, for example:

Premise 1: "Apple left of pear"

Premise 2: "Pear left of mango"

Premise 3: "Mango left of kiwi"

Participants were instructed to imagine the arrangement determined by the premises (in this case apple–pear–mango–kiwi). Subsequently to premise presentation, participants were asked to define the correct arrangement by typing the initial letters of the named objects using the computer keyboard. After entering the last letter, the trial finished automatically. The next trial started after the participant hit the “return” key. All premises were presented in black on a white background.

Stimuli were generated and presented using Superlab 4.0 (Cedrus Corporation, San Pedro, CA, 1999–2006). The experiment was run on a standard personal computer (Windows XP) with a standard 19" monitor. The program recorded (a) premise reading times (respective time from stimulus onset to key press calling up the next premise), (b) the number of correct responses, and (c) corresponding response times (time from request onset till enter of the last letter).

Results and discussion

Premise reading times. To examine whether premise reading times are contingent upon different premise orders, analysis of variance (ANOVA) with the factors premise number (first, second, third) \times premise order (continuous, semi-continuous, discontinuous), was conducted. Level of significance of all analyses throughout the study was 5%.

ANOVA revealed significant main effects of premise number, $F(2, 38) = 9.99$; $p = .004$; $\eta^2 = .34$ and premise order, $F(2, 38) = 13.44$; $p = .001$; $\eta^2 = .41$, as well as a significant interaction premise number \times premise order, $F(4, 76) = 10.73$; $p = .001$; $\eta^2 = .36$. We are mainly interested in the significant interaction.

Subsequent t -tests (Bonferroni-adjustment: α -levels of .0167 per test) revealed that reading times for second premises in the discontinuous condition were significantly higher than those in the continuous $t(19) = -4.26$; $p < .001$, $d_z = 0.95$, and semi-continuous condition $t(19) = -2.99$; $p = .008$, $d_z = 0.67$.

Reading times for third premises were highest in the discontinuous condition. They differed significantly from reading times in the semi-continuous, $t(19) = -3.26$; $p = .004$, $d_z = 0.73$ and continuous condition, $t(19) = -3.75$; $p = .001$, $d_z = 0.84$, while reading times in the semi-continuous condition were significantly higher than those in the continuous condition, $t(19) = -3.13$; $p = .006$, $d_z = 0.70$. All other results, both for the first premises, as well as for second premises, were non-significant (all $ps > .05$). See Figure 1 for illustration.

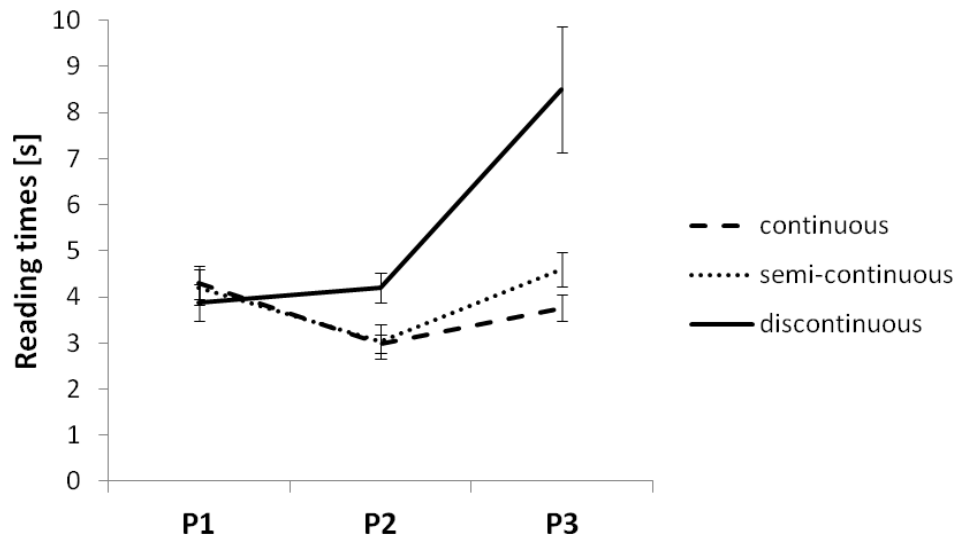


Figure 1. The “continuity effect” as it occurs in the construction phase. The figure shows experiment 1’s mean reading times for the three premises (P1, P2, P3) depending on the premise orders continuous, semi-continuous, and discontinuous. Error bars show standard errors.

Reasoning accuracy and speed. Percentages of correct responses and corresponding response times were compared depending on different premise orders (continuous, semi-continuous, and discontinuous), calculating separate ANOVAs.

Percentages of correct responses, $F(2, 38) = 9.9$; $p < .001$; $\eta^2 = .34$, as well as corresponding response times, $F(2, 30) = 8.42$; $p = .001$; $\eta^2 = .36$ differed significantly depending on the respective premise orders.

Participants defined significantly less frequently the correct arrangement ($M = 59\%$; $SD = 37.3$) when the premises were presented in a discontinuous order, than for continuous ($M = 92\%$; $SD = 6.5$), $t(19) = 3.99$; $p = .001$, $d_z = 0.89$ and semi-continuous premise order ($M = 79\%$; $SD = 28.4$), $t(19) = 2.8$; $p = .011$, $d_z = 0.63$. In contrast, performances did not differ between continuous and semi-continuous orders, $t(19) = 1.83$; $p = .082$.

However, participants needed significantly less time to define the correct arrangement when premises were presented in a semi-continuous order ($M = 1.01s$; $SD = 0.31$) than for continuous ($M = 1.17s$; $SD = 0.48$), $t(17) = 2.84$; $p = .011$, $d_z = 0.58$ and discontinuous premise orders ($M = 1.24s$; $SD = 0.44$), $t(15) = -3.87$; $p = .002$, $d_z = 0.19$. Response times between continuous and discontinuous premise orders did not differ significantly, $p > .15$.

Our results are in line with previous findings concerning the continuity effect. People need more time to process pieces of information that are not related (discontinuous condition) to previously given information than for related information (continuous and semi-continuous conditions). Furthermore, more errors occur in the “unrelated” condition. Up to now, it is assumed that these findings are a result of the disability to integrate sequentially new information into an existing mental model and the necessity to hold given information separately in mind. However, it is not clear yet in which form discontinuously presented information is processed and stored in memory.

The continuity effect of experiment 1 was obtained under the condition that the models were constructed from left to right. The second experiment resembled the first experiment, but with the working direction reversed. Note that the working direction from right to left required for the construction of the models in combination with different premise orders in the second experiment is a novelty that has not been studied before. We expected that reasoners find it more difficult to work in the culturally non-preferred right-to-left direction than in the culturally preferred left-to-right direction. In a case where the continuity effect results from the integration of two separately constructed mental models that are at first held in memory and later united into one common model, the working direction (left to right vs. right to left) should not matter (see the first hypothesis phrased above). In this case, experiment 2 should also yield a continuity effect. In contrast, in a case where the continuity effect is based on the revision (according to the information provided by the third premise) of a model that was preliminarily constructed from the first and the second premises, the working direction matters, and experiment 2 should not yield the continuity effect (see hypothesis 2).

Experiment 2

Method

Participants. A new sample of 26 participants from the University of Giessen (8 male; age: $M = 24.5$; $SD = 3.5$) were tested. The same conditions as those in experiment 1

applied. Data from five participants were excluded from the analysis due an extreme number of errors (more than 98%).

Materials, procedure, and design. The instructions on the computer and the procedure were the same as those in experiment 1. Problems were presented in different premise orders (continuous, semi-continuous, and discontinuous) using the relation "right of" resulting in a working direction from right to left. The same dependent variables as those previously were of interest.

Here is an example trial (continuous order):

| | | | |
|------------|-----------------------|-----|-----------------------|
| Premise 1: | "Apple right of pear" | M1: | pear–apple |
| Premise 2: | "Pear right of mango" | M2: | mango–pear–apple |
| Premise 3: | "Mango right of kiwi" | M3: | kiwi–mango–pear–apple |

Results and discussion

Premise reading times. For reading times an ANOVA with the factors premise number (first, second, third) \times premise order (continuous, semi-continuous, and discontinuous) was conducted.

ANOVA revealed significant main effects of premise number, $F(2, 40) = 4.62$; $p = .031$; $\eta^2 = .19$ and premise order, $F(2, 40) = 3.51$; $p = .039$; $\eta^2 = .15$, as well as a significant interaction premise number \times premise order, $F(4, 80) = 3.70$; $p = .008$; $\eta^2 = .16$. Again, we are mainly interested in the significant interaction.

Premise reading times depending on different premise orders were compared separately using t -tests (Bonferroni-adjustment: α -levels of .0167 per test). Participants needed more time for reading third premises of discontinuous than of continuous, $t(20) = -3.31$; $p = .004$, $d_z = 0.72$, as well as marginally of semi-continuous orders, $t(20) = -2.36$; $p = .028$, $d_z = 0.52$. All other differences were non-significant (all $ps > .08$) (see Figure 2).

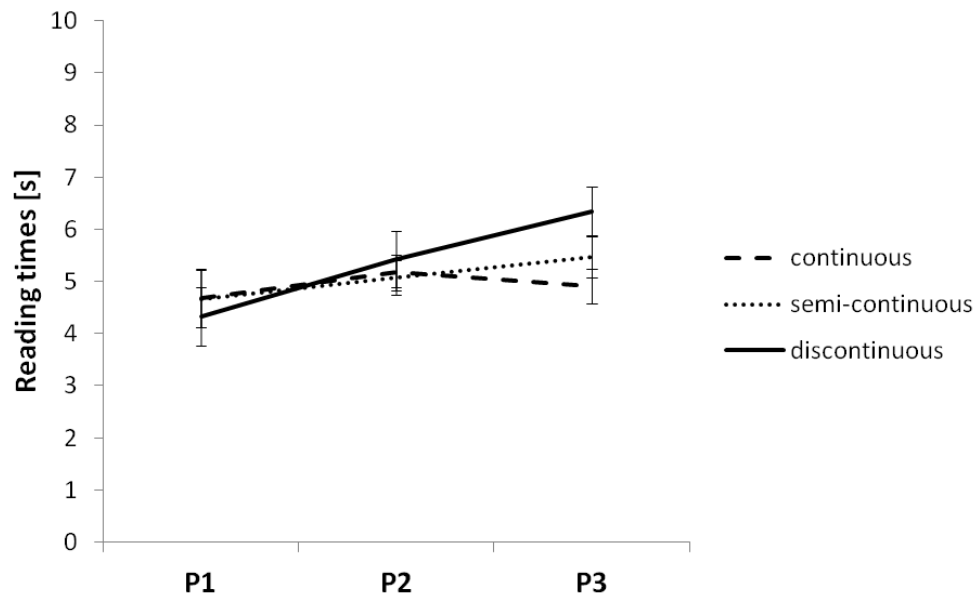


Figure 2. The figure shows experiment 2's mean reading times for the three premises (P1, P2, P3) depending on the premise orders continuous, semi-continuous, and discontinuous. Error bars show standard errors.

Reasoning accuracy and speed. Percentages of correct responses and corresponding response times were compared depending on different premise orders (continuous, semi-continuous, and discontinuous) calculating separate ANOVAs.

Percentages of correct responses differ significantly depending on respective premise orders, $F(2, 40) = 3.57$; $p = .037$; $\eta^2 = .15$. Subsequent t -tests revealed that participants entered correct arrangements significantly less often when premises were presented in a semi-continuous order ($M = 82\%$; $SD = 16.0$) than in a discontinuous premise order ($M = 88\%$; $SD = 11.1$), $t(20) = -2.47$; $p = .022$, $d_z = 0.54$. Additionally, performances differ marginally significantly between semi-continuous and continuous premise orders ($M = 87\%$; $SD = 11.7$), $t(20) = 2.02$; $p = .057$, $d_z = 0.44$. Percentages of correct responses between continuous and discontinuous premise order, as well as response times did not differ (all $ps > .15$).

Please note that the increase in third premise reading times in the discontinuous condition compared to the more continuous conditions cannot be interpreted as continuity effect since data suggest a speed–accuracy trade-off effect (more accurate performance along with the longer reading times). The continuity effect was presumably counteracted

by the working direction from right to left. Although processing third premises in the discontinuous condition took the most time, a closer look at all remaining reading times reveals that there was an overall and very consistent increase of reading times. In particular, second premise reading times increased considerably in the continuous and semi-continuous conditions, and furthermore third premise reading times increased in the continuous condition. Compared to experiment 1, where the increase occurred very specifically for the discontinuous condition, the results of experiment 2 shows an overall increase of difficulty. We suggest that increased difficulty, reflected by the reading times, is not specifically accounted for by the special condition given with discontinuous problems. Instead, it seems that the (non-preferred) working direction from right to left rendered problems more difficult and increasingly difficult.

We conclude that the continuity effect is based not only on the degree of continuity but also on the working direction in which continuously presented pieces of information are integrated. The findings are in line with the hypothesis that one preliminary model is constructed, even when the description is discontinuous. The data do not support the hypothesis that two separate models are constructed and held in memory for later integration.

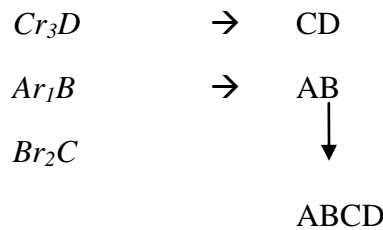
Our results from experiments 1 and 2 suggest two crucial points – mental processing of not related spatial information is associated with more cognitive effort, and, second, continuity effects can be modulated by different working directions. It seems that a working direction from right to left inhibits construction processes, although information is continuously presented, and thus a sequentially integration is possible.

Experiment 2 already challenges the assumption that humans keep two models separately in working memory, when information of one model is not related to information of another, and create an integrated model afterwards (Ehrlich & Johnson-Laird, 1982; Knauff et al., 1998). Based on the results so far, it seems more reasonable to put forward the hypothesis that reasoners deal with ambiguous descriptions by constructing a single model and modifying it if necessary (Knauff et al., 1995; Rauh et al., 1997; Ragni et al., 2005; Rauh et al., 2005).

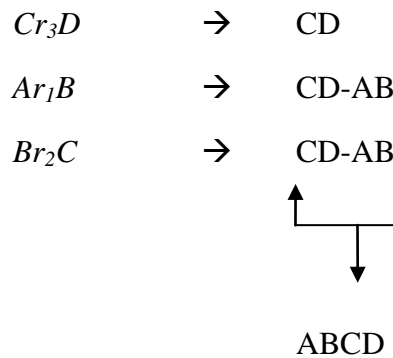
Results from experiment 2 lead to the assumption that discontinuously presented information is integrated into one model, with a preferred working direction from left to right. If this is the case, it is reasonable that performance differences are not caused by cognitive effort for holding and integrating two separate models, but rather by a modification of the preliminary model.

Experiment 3 compares the following possibilities:

1. Two models are held separately and integrated subsequently into one model



2. Information is integrated into one preliminary model (which is revised according to the information provided by the third premise)



To test which principle (1 or 2) applies, we presented two types of similar problems based on either discontinuous (Cr_3D , Ar_1B , Br_2C) or quasi-discontinuous (Cr_3D , Ar_1B , Dr_2A) premise orders. Both types have in common that two sequentially presented premises do not relate the terms presented by them, and these are followed by a third premise that links the terms

Based on previous findings (and experiment 1 and 2) we assume that humans integrate spatial information preferably from left to right into a horizontal linear order (De

Soto et al., 1965; Huttenlocher, 1968; Chan & Bergen, 2005; Spalek & Hammad, 2005). With regard to the results from our second experiment, this would suggest that reasoners would preferably construct C–D–A–B as a preliminary model for both problems. For quasi-discontinuous problems this model can be confirmed when reading the third premise, while for discontinuous problems the model is inconsistent (C–D–A–B) and has to be revised to fit the information of all the premises. Thus, both spatial descriptions result in different arrangements (C–D–A–B for the quasi-discontinuous order and A–B–C–D for the discontinuous order). Continuous problems were not presented in experiment 3 in order to rule out that the preference of working from left to right was aggravated (or even triggered) by the easy and straightforward from left to right constructible models, based on continuous descriptions.

Taken together, we expect the results to be different depending on which principles reasoners apply: In cases where reasoners apply principle (1), the model construction for discontinuous and quasi-discontinuous problems will take the same time, and, in addition, no performance differences will occur. In cases where reasoners apply principle (2), quasi-discontinuous trials will take considerably less time and result in more correct responses than discontinuous trials.

Experiment 3

Method

Participants. A new sample of 25 students from the University of Giessen (3 male; age: $M = 24.0$; $SD = 2.6$) were tested individually. The same conditions as those in the previous experiments applied. The data from five participants were excluded from the analysis due an extreme number of errors (more than 98%).

Materials, Procedure, and Design. Each participant solved 32 determinate 4ts-problems. Again, four practice trials (not analyzed) preceded the experimental trials. The structure of the trials and the procedure were comparable with those of experiment 1 and 2, whereby premises were presented in the two orders, discontinuous and quasi-discontinuous, using the relations “left of” and “right of”.

The same dependent variables as those previously (reading times, number of correct responses and respective response times) were of interest.

Results and Discussion

Premise reading times. An ANOVA with the factors premise number (first premise, second premise, third premise) \times premise order (quasi-discontinuous, discontinuous) was conducted.

ANOVA revealed a significant main effect of premise number, $F(2, 38) = 25.4$; $p < .001$; $\eta^2 = .57$, as well as a significant interaction premise number \times premise order, $F(2, 38) = 16.9$; $p < .001$; $\eta^2 = .47$. Premise orders did not differ significantly ($p = .062$).

T-tests revealed significant longer reading times of third premises of discontinuous ($M = 9.36$ s; $SD = 3.45$) than of those of quasi-discontinuous orders ($M = 7.32$ s; $SD = 2.66$), $t(19) = -3.79$; $p = .001$, $d_z = 0.85$ (see Figure 3). All other differences were non-significant (all $ps > .05$).

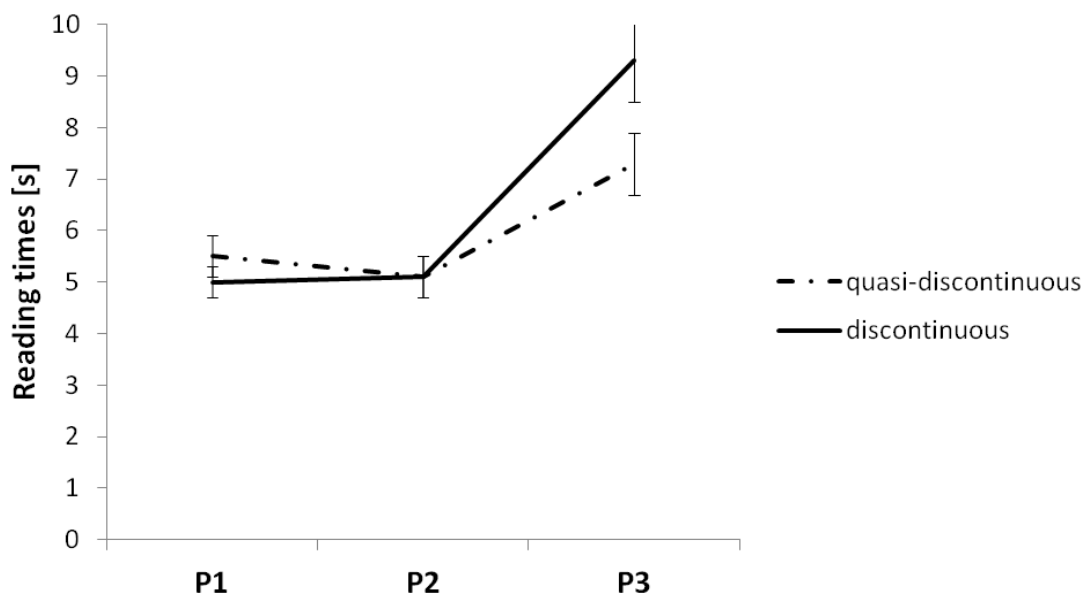


Figure 3. Mean reading times for the three premises (P1, P2, P3) depending on the premise orders quasi-discontinuous and discontinuous (experiment 3). Error bars show standard errors.

Reasoning accuracy and speed. Percentages of correct responses and corresponding response times were compared depending on different premise orders

(discontinuous vs. quasi-discontinuous) calculating separate ANOVAs. Level of significance was 5%.

Percentages of correct responses differ significantly depending on respective premise orders, $F(1, 19) = 6.3$; $p = .021$; $\eta^2 = .25$. Participants defined the correct arrangement in 81% of the cases ($SD = 18.7$), when premises were presented in a quasi-discontinuous order, in contrast to arrangements based on discontinuously presented premises 67% ($SD = 27.1$), $t(19) = 2.51$; $p = .021$, $d_z = 0.56$. ANOVA for response times revealed no significant differences regarding the presented premise orders ($p > .25$).

Taken together, participants needed less time for processing third premises in the quasi-discontinuous condition. Additionally, they constructed arrangements that were more often correct than in discontinuous premise order problems. These findings suggest that different processes are involved when mental models are constructed based on a discontinuous or quasi-discontinuous premise order. The hypothesis, stating that separate models are constructed and held in memory for later integration, would have been supported by results that indicate that reasoners perform comparably in the discontinuous and quasi-discontinuous conditions.

More precisely, the results from our third experiment suggest that humans process discontinuous problems by creating one preliminary mental model (which is modified if necessary), rather than by creating two independent models that are united at a later point in time. With both discontinuous and quasi-discontinuous problems, single models are constructed from the first two premises, which are then checked for consistency in the light of the third premise. The integration of the third premise information requires a higher cognitive load with discontinuous problems, which have to be revised (and objects within the preliminary model relocated). Third premise integration with quasi-discontinuous problems where the preliminary model just needs to be confirmed creates a comparably lower cognitive load. Basically, our results suggest that the underlying construction processes do not differ fundamentally between discontinuous information and more continuous information – in both cases one representation is constructed with a preferred working direction.

However, strictly speaking, the results of the preceding experiments could still be explained by the assumptions made by hypothesis 1 – that is, the construction of two partial models that are held separately and structurally independent in memory. Given that humans construct spatial mental models in a horizontal linear order with the preferred starting point at the left side, this suggests that the first partial model, PM1 (C–D) is to the left of the second partial model, PM2 (A–B). In this case, there is no need for the modification of an arrangement constructed according to a quasi-discontinuous description. Nevertheless, in both cases the two partial models require the integration into one unified model. In this case, the differences in processing would result from the more difficult modification required by discontinuous premises. At this point the question arises of whether there are differences between the postulated preliminary mental model and two partial models that are structurally independent (not connected) but specified in terms of their spatial relation.

Our fourth experiment addresses the above point and the question of how “preliminary” models differ from “final” mental models. To that end, we looked at the “way” the second premise is integrated into a model constructed from a discontinuous description. In fact, it is not clear in which way the information of the second premise will be integrated. But since the reasoner does not have any information where to integrate the new information, he will have to guess. Results from the second and third experiments suggest that information in such a case is integrated to the rightmost end of the model, constructed from the first premise. As mentioned before, it is assumed that spatial information is translated into spatial mental models in which tokens are connected to each other (Johnson-Laird, 1983). For all premise orders, this suggests that after presenting the first premise, given information is represented as a spatial mental model (M1).

For the subsequent construction process two crucial points are assumed: (a) Unrelated information of the second premise (discontinuous and quasi-discontinuous premise orders) is translated into an additional mental model (PM2), because it is not possible to integrate them into the existing model (PM1), and (b) this new mental model is

placed mentally to the right of the mental model of the first premise. Experiment 4 investigates the precise nature of the connection between the two partial models:

We hypothesize that the nature of the connection between the two partial models is describable by either of the following principles:

1. The link that connects the two partial models, PM1 and PM2 of the preliminary model (M preliminary) is as strong as the link that connects the entities within the partial models C-D and A-B.
2. The link that connects the entities within a partial model (C-D and A-B) is stronger than the link that connects two partial models (PM1, and PM2)

In cases where principle 1 applies, it can be expected that single entities (A, B, C, or D, respectively) are preferably relocated during the last step of the construction process, rather than partial models (that consist of two entities, A-B or C-D). In cases where principle 2 applies, we expect the relocation of partial models rather than single entities.

Experiment 4

Method

Participants. A new sample of 21 participants from the University of Giessen (6 male; age: $M = 23.0$; $SD = 6.9$) were tested individually. The same conditions as those for the previous experiments applied.

Materials, procedure, and design. The instructions and the procedure were the same as those in experiment 3. Each participant solved 64 determinate 4ts-problems using the relations “left of” and “right of” and again we manipulated the premise order (discontinuous: Cr_3D, Ar_1B, Br_2C) or quasi-discontinuous: Cr_3D, Ar_1B, Dr_2A). Six practice trials (not analyzed) preceded the experimental trials. In contrast to experiment 3, we modified the premise orders in a way that the third premise described all possible connections between the named terms of premise 1 and 2. This manipulation allows to test

whether links that connect partial models are as strong as links within partial models. For an overview of all used third premises in experiment 3 and 4 see table 2.

Table 2

Overview of formulations of the third premise in experiment 3 and 4 (M preliminary that is constructed on the basis of premise 1 an 2)

| | Experiment 3 | | Experiment 4 | |
|----------------------|-----------------------------|-----------------------------|--|--|
| | discontinuous | quasi-discontinuous | discontinuous | quasi-discontinuous |
| <i>M preliminary</i> | CDAB | CDAB | CDAB | CDAB |
| Premise 3 | B left of C C right of B | D left of A A right of B | B left of C C right of B A left of C C right of A B left of D D right of B A left of D D right of A | B right of C C left of B A right of C C left of A B right of D D left of B A right of D D left of A |

The same dependent variables as those previously (reading times, number of correct responses and respective response times) were of interest. Additionally the number of relocated terms in the discontinuous condition was analyzed.

Results and discussion

Premise reading times. To analyze the reading times with regard to the respective premise orders (discontinuous vs. quasi-discontinuous) and the premise number (first, second and third) an ANOVA was conducted.

ANOVA revealed significant main effects of premise number, $F(2, 40) = 14.55$; $p = .001$; $\eta^2 = .42$ and premise order, $F(1, 20) = 9.58$; $p = .006$; $\eta^2 = .32$, as well as a significant interaction premise number \times premise order, $F(2, 40) = 11.48$; $p = .001$; $\eta^2 = .37$. Again we focus on the significant interaction.

T-tests revealed significant longer reading times of third premises of discontinuous ($M = 8.02$ s; $SD = 3.63$) than of quasi-discontinuous premise orders ($M = 6.27$ s; $SD = 2.83$), $t(20) = -3.61$; $p = .002$, $d_z = 0.79$. All other differences were non-significant (all $ps > .40$).

Reasoning accuracy and speed. Percentages of correct responses and corresponding response times were compared depending on different premise orders (discontinuous vs. quasi-discontinuous), calculating separate ANOVAs. Neither numbers of correct responses (discontinuous: $M = 75\%$; $SD = 22.8$; quasi-discontinuous: $M = 79\%$; $SD = 15.7$), nor corresponding response times (discontinuous: $M = 1.07$ s; $SD = 0.32$; quasi-discontinuous: $M = 1.03$; $SD = 0.30$) differ significantly between both premise orders (all $ps > .25$).

Going a step further by comparing percentages of given responses based on relocated partial models versus separate entities in the discontinuous condition, ANOVA revealed significant differences, $F(1, 19) = 105.72$; $p < .001$; $\eta^2 = .85$. Thus, results show that entered arrangements include in 92% of the cases ($SD = 18.1$) entered arrangements include all the connections between the named terms described by the premises, whereas in only 8% ($SD = 18.1$) of the cases single entities were relocated, $t(19) = 10.28$; $p < .001$, $d_z = 2.30$. For an illustration see Figure 4. The left bar indicates the cases where partial models (consisting of two entities) were relocated, resulting in the arrangement A–B–C–D (principle 2), as opposed to the cases where relocations of a single entity were performed (principle 1).

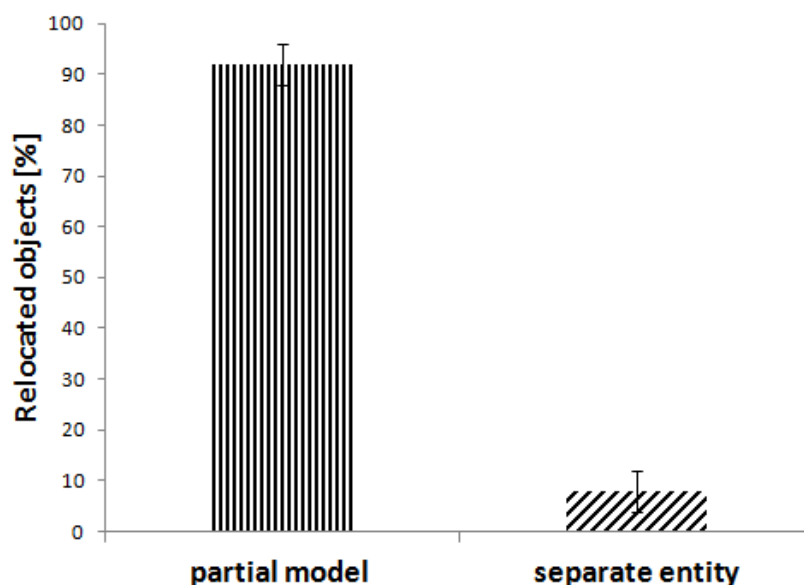


Figure 4. Percentage rates for given responses in the discontinuous premise order, based on a relocation of a completely partial model compared to a single entity in experiment 4. Error bars show standard errors.

To investigate characteristics of the postulated preliminary model that is constructed in cases of unrelated spatial information, we conducted a fourth experiment. Generally it can be described as a mental model that consists of coherent and determinate partial models, reflecting the information of two or more discontinuously presented premises. The partial models are sequentially integrated to the rightmost side of an existing model (at least as long as there are no alternative instructions). New partial models are connected by a temporary link that is not as strong as the connections between the actually directly related objects. In cases where additional information confirms the preliminary arrangement, this link is translated into a connection that resembles an already existing link within a partial model. In cases where new information suggests a rearrangement of the preliminary model, cognitive effort is needed to relocate a partial model and to connect them, using newly created links.

General discussion

Construction processes of spatial mental models from premises are influenced by various factors. Our study focuses on the question of how spatial mental models are constructed, especially with regard to discontinuous information. The main question we followed is whether humans construct *more than one model*, with the first two premises presented in a discontinuous description, and integrate the models only later into a unified representation, with the last part of the description, or whether they construct *one* preliminary model, regardless of the continuity of the premise orders, and modify it in the light of the third premise. Our results support previous findings regarding the continuity effect. They add to the body of evidence that dealing with discontinuous information is more difficult than dealing with information presented in a continuous or semi-continuous order. However, so far it was assumed that the reason for these differences is caused by cognitive effort needed to represent and integrate two separate models. The present study supports an alternative hypothesis, which states that reasoners actually integrate information provided by the premises into one preliminary model, which is modified if necessary as the description continues.

The results from Experiments 1 and 2 demonstrate that humans construct spatial mental models preferably in a left to right manner, and that two main factors can increase the cognitive effort for underlying construction processes: The direction in which new objects can be integrated into an existing model modulates the complexity of construction processes, as well as the number of objects that have to be relocated within a mental model. This finding is in line with previous results showing that humans need more time in cases where two objects are relocated within a mental model than for the relocation of a single object (Bucher & Nejasmic, 2012).

Results of the third experiment suggest that different processes are involved when mental models are constructed on the basis of discontinuous and quasi-discontinuous problems. It is easier to construct mental models in quasi-discontinuous than in discontinuous orders. The results support the hypothesis that in both cases a preliminary model is constructed for the first two premises, rather than two separate models. The preliminary model is then inspected for consistency in the light of the third premise. This procedure implies that the construction of spatial mental models based on discontinuous premise orders is in principle the same as that for more continuous ones. More precisely, for discontinuous descriptions, just as is the case for continuous descriptions, one preferred mental model is constructed. However, in the case of the discontinuous problem, the model can be inconsistent (C–D–A–B) and thus has to be revised to be consistent with all given premises (A–B–C–D). Hence, processing difficulties are a result of the modification of this preliminary model and the number of objects that have to be relocated within this preferred model. For the discontinuous condition this would imply that two objects have to be relocated to the leftmost side. As mentioned before, the number of relocated objects and the direction of the relocation within a mental model influence humans' performance. Especially the results of the second experiment support these assumptions, showing that participants had more difficulties in constructing a mental model when a working direction from right to left was suggested. For instance, based on these assumptions, participants in experiment 1 had to relocate two objects in a discontinuous condition to the leftmost side,

resulting in more cognitive effort than in the semi-continuous condition where only one object had to be placed into the “non-preferred” leftmost side.

Following the assumption that humans construct just one preliminary mental model in discontinuous cases, we investigated characteristics of such preferred spatial mental models. Results suggest that the main characteristics of these preliminary mental models do not differ essentially from those of “regular” mental models. The crucial difference is the temporary link between the two parts within a preliminary model that reflect the information from Premises 1 and 2. It seems that humans prefer also in discontinuous cases a construction direction from left to right and insert, notwithstanding the lack of clear instructions, additional, independent information into an existing mental model with an annotation of a temporary link. When new pieces of information support this temporary relation, it is changed into a “regular” and final model. Otherwise, entities have to be relocated within the preliminary model in order to regain consistency between this preliminary model and the additional information. The postulated single preliminary mental model that is varied when necessary, as opposed to the construction of multiple models, fits well with the principle of parsimony and with previous findings suggesting that humans prefer to construct as few mental models as possible (Knauff et al., 1995; Rauh et al., 1997; Ragni et al., 2005; Rauh et al., 2005; Ragni et al., 2006; Krumnack et al., 2011; Ragni & Knauff, 2013).

We suggest that the principle of parsimony is not restricted to spatial descriptions and n-term series problems like those used in the present study. There is evidence that humans more generally prefer to integrate new entities into an existing mental model rather than to construct multiple models, and it does not matter whether the mental model is a “regular” or a preliminary one. For instance, in cases where reasoning is about non-spatial relations (e.g., “thinner than” or “more beautiful than”) instead of spatial relations, humans still order objects spatially. We assume that in the cases of non-spatial relations, humans would still construct preliminary mental models, in accord with the same principles as those applied in the cases of spatial relations – that is, the principle of parsimony, and where possible with a working direction from left to right. The basis for this assumption is

converging evidence that the parietal cortex is a common brain structure, activated in both reasoning processes based on mental models and processing of spatial information. Consistently, there are various findings that spatial effects also occur with non-spatial relations and non-spatial content (Knauff, 1999; Prado, van der Henst, & Noveck, 2008; Prado, Chadha, & Booth, 2011; Knauff, 2013). To what extent reasoning outside the spatial and relational domain is organized spatially (e.g., when categorical syllogisms are processed) is still a matter of debate (e.g., Goel & Dolan, 2001; Knauff, 2013).

The principle of parsimony might be accounted for by characteristics of the working memory where information, such as that provided by the premises in our study, is held for processing and manipulation. Given the limitation of the working memory capacity, it seems necessary that working memory content is held in reasonably “compact” formats, using “chunking” strategies (i.e., entities supposed to be remembered are clustered in order to make efficient use of the limited working memory capacity) or economic representations such as those reflected by our finding of the construction of a minimal number of mental models. In this context, we have to emphasize that it matters in what way the pieces of information that describe a situation are accessible to a reasoner, in particular, whether all pieces of information are available simultaneously or only sequentially, one at a time, as it is the case in our study. The sequential presentation of premises in our study created the need to hold the information provided by previously presented premises in working memory while integrating the information from the following premises. We assume that results of our experiments would look different if there was no need to keep unrelated information in mind – for example, in cases where all the premises are presented simultaneously. Most likely a reasoner would try to get an overview before she constructs the final mental model based on all the information relevant to solving the task. However, when an overview is not possible (as in our experiments), humans seem to merge unrelated information into a preliminary mental model in order to have more cognitive resources available for premise processing, with the consequence that subsequent additional processes are needed to modify this preliminary mental model. The more demanding a task, the more it is necessary to be economical with

cognitive resources. Economic processing is, certainly among other economic procedures, achieved by avoiding strategy switches during a problem-solving procedure. Instead, reasoners might stick to a strategy that had been applied successfully previously in the process. For instance, the way humans construct mental models under high task demand influences how they revise this mental model subsequently. Under high task demand, reasoners are more likely to use one and the same strategy for constructing and revising a mental model. Under low task demand, however, reasoners can “afford” (in terms of cognitive resources) to switch strategies between construction and revision (Nejasmic, Bucher, Thorn, & Knauff, 2014).

A pivotal role might be played by the complexity of a task. The complexity of a task increases with the number of items, chunks, or units of information that are involved in this task (Miller, 1956). With relational problems, the crucial role is played by relational complexity (Halford et al., 1998; Phillips & Niki, 2002). Relational complexity results from interactions of components such as the number of objects, relations, and the type of relation (binary, ternary, quaternary, and so on). Complexity draws on processing capacity – that is, the more complex a problem is, the more cognitive resources are required to solve it. Processing capacity or cognitive resources rely on working memory capacity, with the working memory required to maintain and manipulate the pieces of information relevant to solving the task (Hitch, 1980). The demand for processing a certain task is measurable by – for instance – the decrement of performance in comparison to another, less complex, task. The less complex and less difficult a task, the fewer resources are required to be allocated, which in turn is reflected by less processing time and/or fewer errors than in a more complex/ difficult task (Navon & Gopher, 1980). Accordingly, the high demand on cognitive resources for discontinuous problems as it is reflected by the continuity effect is accounted for by the complexity of these problems. The high complexity of discontinuous problems compared to more continuous ones is presumably caused by the necessity to process all relations within the preliminary model, before revision according to the last piece of information (here, the third premise) can be accomplished. In this sense, the

principle of parsimony can be regarded as a strategy to deal with the complexity and reduce cognitive effort.

Our findings are also interesting in an even more practical domain of everyday life – that is, language processing and in particular text comprehension. For discourse comprehension, it is essential that new information is referred back to previously given information, otherwise humans have a hard time to understand the text content (van Dijk & Kintsch, 1983; Ferstl & von Cramon, 2005; Ferstl, 2010). It can be said that discontinuous problems in the present study are an example of such referential discontinuity, and it seems plausible that humans try to construct one preliminary representation of the given information, despite the lack of unambiguous clarity. The process of text comprehension and model construction is certainly supplemented by general knowledge (Hagoort, Hald, Bastiaansen, & Petersson, 2004, Hagoort & van Berkum, 2007), and presupposes the preparedness to revise this preliminary mental model in the light of determinate information. By doing so it is possible to hold given information in a parsimonious way in working memory. However, it must be mentioned here, that such a procedure might be a cognitive economical strategy, but carries also the risk of constructing flawed representations. One possible explanation why errors occur is that the general knowledge and a first preliminary model have been strongly mixed up, so that it is not possible to divide them in the light of determinate information. Another possibility is that humans fail to revise their initial uncertain representation and adhere to it (regardless of the reasons for this failure). An inversion of this scenario is that working memory limitations might constitute poor readers, and vice versa, because more cognitive resources are needed to process and integrate not related information, and, due to this higher cognitive load, preliminary representations are incorrectly processed (Just & Carpenter, 1992; Mähler & Schuchardt, 2012). False information or invalid conclusions might be the results.

Taken together, the present results fit well with investigations and assumptions concerning working memory limitations (Halford et al., 1998; Sanford & Garrod, 2005). The idea of one preliminary mental model in spite of discontinuous information supports earlier studies showing that humans experience difficulties when the complexity of a task

increases. This may include an increased number of objects that have to be processed, switching from different relations or working directions, as well as a multidimensionality of a mental model that has to be constructed. The more information that is required to be actively manipulated in working memory, the more complex a task can be considered. Investigations show that humans handle such situations by the use of more efficient strategies, like conceptual chunking or segmentation of tasks with the aim to make better use of limited capacities, whereby it is possible to switch between strategies, according to actual requirements (Halford et al., 2007). The construction of single (preliminary) mental models in spite of uncertain information is certainly an economical cognitive strategy. Our results offer a new view on the continuity effect and the fundamental principles of model construction and variation in human spatial reasoning.

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Part 2

Chapter 2

Cognitive processes underlying Spatial Belief Revision²

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Abstract

New information sometimes contradicts what is believed about certain states of the world. To integrate contradicting information, reasoners have to revise existing beliefs. In the course of belief revision they need to decide which beliefs to retain and which ones to retract in order to regain consistency within current belief states. What guides belief revision has been studied in the non-spatial domain. Based upon previous work on spatial reasoning, we develop hypotheses about the cognitive processes of belief revision in spatial reasoning. Spatial beliefs are considered to be based on spatial mental models that are subject to variation during revision. We provide empirical evidence that models are varied according to information provided by inconsistent statements rather than processes vital for construction of initial models. Furthermore we show that revising spatial models follows dissociable principles from constructing initial spatial models.

Introduction

Imagine the following situation: You look for an apartment to buy when two friends of yours tell you about a nice place offered by the local real estate agency. A says: "There is parquet floor either in the lounge or in the bed room, but not in both rooms." B says: "There is parquet floor in the bed room." As a matter of fact you get the information from the real estate broker: "There is parquet floor in the lounge." Given the broker knows what he sells, either A's or B's statement must be wrong. Which statement do you believe is true – A's or B's? Whom do you believe – A or B? Processes that guide this decision are subject to belief revision research. Belief revision is an everyday task that describes the process reasoners perform in order to regain consistency when confronted with new information that is inconsistent with existing beliefs. Generally, it requires knowledge about the entities reasoned about, e.g. such that two entities cannot reside within the same spatio-temporal coordinates. Furthermore, belief revision might be affected by numerous factors such as familiarity with the entities or trustworthiness of speakers uttering the information (Wolf & Knauff, 2008). Here, we study belief revision in reasoning about objects that are neutral regarding these factors. Specifically, we look at

factors that play a role in the initial construction of spatial mental models and carefully examine their potential role in processes during revision of these initially constructed models. The processes that guide belief revision in the spatial context have not been investigated so far. Based on what is known about reasoning with spatial mental models (Byrne, 1998; De Vooght & Vandierendonck, 1998; Klauer, 1998; Schaeken, Girotto, & Johnson-Laird, 1998; Goodwin & Johnson-Laird, 2005), we develop hypotheses about cognitive processes that might be vital for belief revision in spatial reasoning. Empirical evidence culminates to the assumption that spatial reasoning relies on the construction, inspection, and variation of spatial mental models (Knauff, Rauh, & Schlieder, 1995; Rauh, Schlieder, & Knauff, 1997, Knauff, Rauh, Schlieder, & Strube, 1998). We briefly summarise relevant work on spatial reasoning and come up with hypotheses about belief revision in the spatial domain. Subsequently, we report empirical evidence from two experiments that tested these hypotheses and discuss implications of the results.

Construction and inspection of spatial mental models

Consider the following spatial description that determines the linear arrangement of three objects:

- (1) The apple is left of the pear.
- (2) The mango is left of the apple.

Sentences of this kind are called premises, from which a mental model can be incrementally constructed by successively integrating information. Starting with the first premise (1), the two objects are arranged according to the relations and result in the following model (M1),

(M1) apple – pear

Successively, the information from the second premise (2) is integrated, resulting in the model (M2):

(M2) mango – apple – pear

By inspection of this model new information can be inferred. Relational inference processes enable reasoners to make decisions about whether the following statements are true.

(3) The mango is left of the pear.

(4) The pear is left of the mango.

The sentences (3, 4) that have to be checked for validity are usually referred to as conclusions. Conclusion (3) is valid, i.e. it is consistent with the information provided by the premises and the model (M2), while as a conclusion (4) is invalid, i.e. it is inconsistent with the information of one of the premises and the model.

Inconsistency detection

An inconsistency typically arises from a conflict between a (valid) conclusion (e.g. “the mango is left of the pear.”) and contradicting evidence (e.g. if you know that as a matter of fact “the pear is left of the mango.”). Reasoners are able to detect inconsistency by inspecting the mental model (e.g. Knauff et al., 1995; Johnson-Laird, Legrenzi, & Girotto, 2004). Inconsistency detection is a prerequisite for belief revision.

Cognitive processes underlying variation of spatial mental models

The question is: what guides revision? Imagine a reasoner realises that his or her conviction about the arrangements of objects in space must be invalid. This problem is presumably solved by varying the initially constructed mental models (Rauh et al., 1997). Knauff et al. (1995), Rauh et al. (1997), Ragni, Knauff, and Nebel (2005) showed that

reasoners deal with increasing complexity induced by ambiguous spatial descriptions that allow for more than one model to be constructed by focusing on only a subset of possible models and often just a single one. If reasoners are asked to create an alternative model that also coheres with the description, they use the following principle: Instead of abolishing the initially constructed model and create a new one from the scratch, alternative models that also cohere the description are preferably created by minor variations of the initially constructed model. We thus assume that mental model revision is accordingly based on variation.

Further, we assume that initial models are varied just as much as necessary to obtain a model that is consistent with all propositions. Conserving as many information as possible is in line with a “minimal change principle” (Gärdenfors, 1984; Harman, 1986). In the present paper, we investigated whether information that guide the construction of initial mental models play a role during the variation of these models. There is evidence that verbatim information from the premises describing a determinate arrangement (i.e. allowing for only one model to be constructed) is not reliably retrievable from memory (Mani & Johnson-Laird, 1982), bolstering the assumption that mental models rather than sentences are stored in memory. That makes sense when taken into account that storing the representation of information in compact models is more parsimonious compared to storing the original information from the description. Thus, storing models facilitates manipulation in memory. However, there is evidence that nevertheless not only the “end product” of a construction process, i.e. an integrated mental model is kept in memory but also vital steps of its construction process (Payne, 1993; Payne & Baguley, 2006). Payne (1993), Payne & Baguley (2006) argue that memory retrieval of spatial arrangements is primarily supported by an “episodic construction trace”. The trace records the mental operations used during vital steps of the construction process, such as the order of objects inserted into the mental model. Subsequent to construction, the inspection phase starts.

A verisimilar assumption is that the starting point for inspection is the object last inserted into the model. This had been shown for spatial mental models using Allen’s calculus (Knauff et al., 1998), providing evidence that operations of construction influence

inspection. The question is whether these operations also influence variation. In this case we would assume that variation is based on the relocation of the object last inserted into the model during the construction phase. However, it is also possible that the revision is not influenced by the construction process. Then the variation of an initially constructed mental model would rely solely on spatial information provided by an inconsistent fact. In each spatial array the spatial information is represented in relational terms.

The binary spatial relations are defined as a triplet (X, r, Y) in which X is called the “to-be-located object” (LO) and Y the “reference object” (RO) (Miller & Johnson-Laird, 1976). LO and RO are located relative to relations “r” such as “left of”, “right of”, and “next to”. If we assume that the revision process is guided by the essential distinction between an LO and an RO stated in a sentence that convey the inconsistent information, we would expect that variation is based on the relocation of the LO while the RO remains located at its initial position. Experiment 1 was designed to test whether revisions are accomplished by following either of the two principles:

1. Relocation of the object last inserted into the model
- vs.
2. Relocation of the LO of the inconsistent fact

In this experiment, the objects’ arrangements described by first and second premises were structured as follows: From the description of the first premise, an arrangement of the two objects and the relation “left of” (e.g. “apple left of pear”) was constructed. The second premise yielded the information to insert a third object into the model such that it was located to the leftmost side of the model (e.g. “kiwi left of apple”, resulting in the model “kiwi – apple – pear”). Thus, the location of the object last inserted into the mental models constructed from the two premises was always in the leftmost position of the arrangement. Consistent conclusive facts (e. g. “kiwi left of pear”), presented in half of the items confirmed the constructed mental models. Inconsistent conclusive facts (e.g. “pear left of kiwi”) required inconsistency detection followed by

model revisions. The facts' structure resembled the premises' structures. Facts also described arrangements of two objects related to each other by using the relation "left of".

Experiment 1

Method

Participants. Twenty-three participants (7 male; age: $M = 22.57$; $SD = 2.92$) with the exception of one all students (among them 6 students of psychology) from the University of Giessen, all reporting normal or corrected-to normal visual acuity, gave written informed consent to participation. Participants were tested individually and were paid at a rate of 8 Euro per hour.

Materials, procedure, and design. Thirty-two items were presented randomly. The items followed a tripartite structure as follows.

Model construction. Two premises (presented sequentially in a self-paced manner) described a one-dimensional (linear) order of three (small, equal-sized, disyllabic-termed) objects, belonging to either one out of four categories (tools, stationery, vegetables, and fruits). Subsequently to premise presentation, participants were instructed to choose the correct order from two alternative orders (correct order and correct order mirrored) that were presented on the left and right side of the computer screen, indicating their choice by pressing a left or right response button with the left or right hand, accordingly. Left and right locations for correct and incorrect orders were counterbalanced across the experiment. Number of correct decisions and corresponding decision times were recorded.

Example:

1st premise: "The apple is to the left of the pear"

2nd premise: "The kiwi is to the left of the apple"

spatial mental model: Kiwi – apple – pear

Inconsistency detection. Subsequently to the participant's decision, a conclusive fact³ (font colour red to contrast the fact with the premises) that was either consistent (in half of the items) or inconsistent (in the other half of the items) with the information provided by the premises, (hence with the order of objects) was presented. In all premises and conclusive facts, we used only the relation "left of".

Participants were instructed to decide whether the conclusive fact was consistent or inconsistent with the order of objects, indicating their decision by pressing the respective response button ("yes" or "no") with the left or right hand, accordingly. Successful inconsistency detection and corresponding detection times were recorded.

Example:

Consistent fact: "The kiwi is to the left of the pear."

→ requires confirmation of the model as correct answer

Inconsistent fact: "The pear is to the left of the kiwi."

→ requires inconsistency detection as prerequisite for belief revision

Belief Revision. If a participant's decision was "no" (i.e. decision that the fact was inconsistent with the information yielded by the premises), he or she was subsequently instructed to indicate how the initial order of the objects would have to be revised in order to be consistent with the inconsistent fact. Participants chose a preferred revised order from two orders presented on the left and right side of the computer monitor by pressing the respective response button. Presentation locations of the two models were counterbalanced across the experiment. In fact, both orders were equally consistent with the information yielded by the conclusive fact and one of the premises (either the initially presented 1st or 2nd premise) while contradicting the respective other premise, complementary. However, they were revised according to different revision strategies. One order resulted from a variation by relocating the object that was last inserted during

³ Facts conveyed implicit information not directly provided by the premises (e.g. "Kiwi left of pear" (consistent) or "Pear left of apple" (inconsistent) with the premises: "Apple left of pear" and "Kiwi left of apple").

the construction phase, referred to as “relocation of last object” in the following. The alternative order was obtained by variation of the initial model according to the inconsistent fact, more precisely by relocation of the inconsistent fact’s LO into the direction indicated by the fact’s relation (“left of”). This revision principle is referred to as “relocation of LO” in the following. Models chosen according to the respective revision principle and corresponding revision times were recorded.

Examples of revised orders:

Apple – pear – kiwi (“relocation of last object”)

vs.

Pear – kiwi – apple (“relocation of LO”)

Four practise trials (not analyzed) preceded the experimental trials. All stimuli were generated and presented using Superlab 4.0 (Cedrus Corporation, San Pedro, CA, 1999) with an RB-530 response pad running on a standard personal computer with a 19”-monitor.

Results and discussion

Based on the information provided by the premises participants chose the correct order of objects in 99% ($SD = 2.27$) of the trials within 1.97s ($SD = 0.75$). Erroneous trials were excluded from further analysis. Inconsistency detection was successful in 92% ($SD = 13.80$) of the trials and took 1.09s ($SD = 0.36$) on average. Erroneous trials were excluded from further analysis. Percentages of revised orders based on “relocation of last object” vs. “relocation of the LO”, respectively and corresponding revision times were compared calculating separate ANOVAs. Level of significance was 5%.

ANOVAs revealed a significant difference for percentages of revision strategies applied, $F(1, 22) = 158.71$; $p < .001$; $\eta^2 = .88$ and revision time, $F(1, 14) = 6.73$; $p < .05$; $\eta^2 = .33$. Revision was significantly more often based on “relocation of the LO” ($M = 88\%$ $SD = 14.38$) than of a “relocation of the last object” ($M = 12\%$; $SD = 14.38$), $t(22) = 12.60$;

$p < .001$. Accordingly, “relocation of the LO” ($M = 4.82$ s; $SD = 2.01$) was significantly faster than “relocation of the last object” ($M = 9.56$ s; $SD = 8.25$), $t(14) = -2.59$; $p < .05$. Results indicate that compared to models based on “relocation of the last object”, models based on “relocation of the LO” were clearly preferable and faster created (see figure 1). This suggests that revision processes operate on fully integrated mental models of the spatial arrangements and are varied in accordance with the inconsistent information.

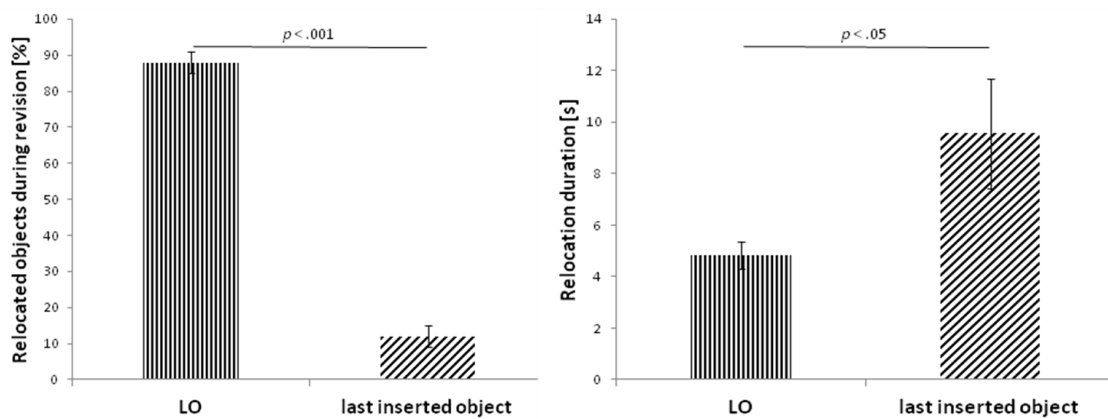


Figure 1. In experiment 1, revision was mainly based on the relocation of inconsistent facts’ LOs. Error bars show standard errors.

However, from experiment 1 we cannot rule out that revision was based on an order effect thus that the object first mentioned in the sentence that conveyed the critical spatial information for the revision task at hand (i.e. the inconsistent fact) guided the variation of the mental model. In order to test for order effects we conducted experiment 2.

Here, we varied the sentence structure of premises and facts in that way that the first mentioned object was not necessarily the LO of a sentence. This experiment actually aims to investigate decisive factors of spatial belief revision. We report a detailed analysis that tested for order effects during the construction part compared to the revision part of the experiment. This analysis was done specifically for the present context in order to compare principles applied during construction and revision, respectively.

Order effects during construction and variation of spatial mental models

We investigated whether construction and/or variation of objects would follow the order of objects as they appear in the sentences conveying the relevant spatial information for the task at hand (i.e. 1st premises for construction and inconsistent facts for revision). Participants' task was to physically construct spatial arrangements based on verbal descriptions and subsequently modify these arrangements after receiving inconsistent information. The physical arrangements allowed us to observe the principles participants applied during construction as compared to revision when manipulating objects within spatial arrangements.

Experiment 2

Method

Participants. Twenty-two participants (5 male; age: $M = 22.59$; $SD = 3.16$) all students (among them 5 students of psychology) from the University of Giessen, all reporting normal or corrected-to normal visual acuity, all but two (one left-handed, one ambidexter) were right-handed, gave written informed consent to participation. Participants were tested individually and were paid at a rate of 8 Euro per hour.

Materials, Procedure, and Design. Thirty-two items were presented, each consisting of two premises and an inconsistent fact on a 19"-computer screen, using Microsoft PowerPoint (Version 2007) running in the windows environment XP on a standard personal computer. PowerPoint slides were presented by the experimenter in a sequentially and individually adapted manner according to participants' performance.

In 8 items, the two premises and the contradictory fact (presented in red) had the surface structure (referred to as sentence structure 1) as follows: First mentioned object (and LO) - relation (either "left of" or "right of") - Second mentioned object (and RO).

Example: "Yellow is to the left of red".

In 8 items, the two premises and the contradictory fact had the sentence structure (referred to as sentence structure 2): Relation – First mentioned object (and RO) – Second mentioned object (and LO).

Example: “To the right of yellow is red”.

In 8 items the two premises followed sentence structure 1 while the fact followed sentence structure 2. In 8 items the premises followed sentence structure 2 while the fact followed sentence structure 1. The relations “left of” and “right of” were used in the premises and in the facts, with the orders as depicted in table 1 below.

Table 1
Relations used in the premises and facts presented in experiment 2

| Relations in the premises and facts in items of experiment 2 | | | | |
|--|--------------------|--------------------|--------------------|--------------------|
| 1 st premise | left of | left of | right of | right of |
| 2 nd premise | left of | right of | left of | right of |
| Fact (inconsistent) | left of / right of | left of / right of | left of / right of | left of / right of |

Participants were provided with wooden square blocks (size: 2.5 x 2.5 x 2.5 cm), red, green, yellow, and blue coloured on a plate in front of them. They were instructed to pick up the coloured blocks, one at a time using one hand, and arrange them according to the information provided by the premises into a linear one-dimensional order. The premises informed about the determinate order of the coloured blocks with the blocks represented by the respective colours (red, green, yellow, and blue).

Example:

1st premise: “To the right of red is blue”

2nd premise: “Green is to the right of blue”

Spatial arrangement: Red – blue – green

All items were constructed such that the third object of an arrangement (whose location was described in the 2nd premise) was located on the rightmost side of an arrangement. However, based on the description of the 1st premise there were two possibilities for constructing the arrangements:

1. Starting on the left side and continue to the right, e.g. (consider the 1st premise from the above example) putting down the red block first and placing the blue block to the red one's right side
2. Starting on the right side and continue to the left, e.g. putting down the blue block first and placing the red block to the blue one's left side

The resulting orders are describable as 1–2–3 and 2–1–3, with the numbers indicating the order by which objects had been put down; e.g. red first–blue second–green third (order 1–2–3) and red second–blue first–green third (order 2–1–3). Subsequently after participants had constructed the order of three coloured blocks, they were asked to revise their order according to an inconsistent fact (e.g. green is to the left of red). Participants were free with the revision of their initially constructed arrangements. The question was whether there would be order effects when constructing or revising the arrangements. If there were, construction would follow the order of the objects as mentioned in the 1st premise. The object mentioned first would be put down first, followed by the second mentioned object. During variation, the object of relocation would be the first object mentioned in the inconsistent fact. Four practise trials (neither recorded nor analyzed) preceded the experimental trials. After each trial, the wooden blocks were put back onto the plate by the experimenter. Performance was recorded online on a video tape by the experimenter and analyzed offline after the experimental session.

Results and discussion

Model construction. Mean percentage rate of correctly constructed models was 98% ($SD = 3.47$). Erroneous trials were excluded from further analysis. Participants

constructed order 1–2–3 ($M = 51\%$; $SD = 4.25$) comparably often as order 2–1–3 ($M = 49\%$; $SD = 4.25$), $F(1, 21) = .96$; $p = .34$; $\eta^2 = .04$.

To test whether the construction order was contingent on the objects as mentioned in the 1st premise we conducted an ANOVA with the factor First mentioned object. The ANOVA revealed a significant main effect, $F(1,21) = 82.84$; $p < .001$; $\eta^2 = .04$. Orders were constructed by putting the first mentioned object of the 1st premise ($M = 83\%$; $SD = 17.15$) before the second mentioned object ($M = 17\%$; $SD = 17.15$). This clearly shows that the principle applied during construction of an initial arrangement was based on the order of objects as mentioned in the 1st premise.

Belief revision. Mean percentage rate of correctly revised orders was 98% ($SD = 3.18$). Erroneous trials were excluded from further analysis. We tested whether an order effect was also present in the variation phase. If it was the first mentioned object of the relevant information (i.e. the inconsistent fact) would be subject to relocation during variation. However, first mentioned objects of inconsistent facts were relocated comparably often ($M = 51\%$; $SD = 7.77$) as second mentioned objects ($M = 49\%$ $SD = 7.77$), $F(1, 21) = .58$; $p = .46$; $\eta^2 = .03$.

Dissimilar to the construction phase, processes of variation did not rely on order effects, implying that different principles were applied for revision than of construction. Figure 2 depicts the results of the construction and the revision phase. Indeed – consistent with results of experiment 1 – we found the principle of revision to be based on the relocation of the inconsistent fact's LO ($M = 90\%$; $SD = 11.30$).

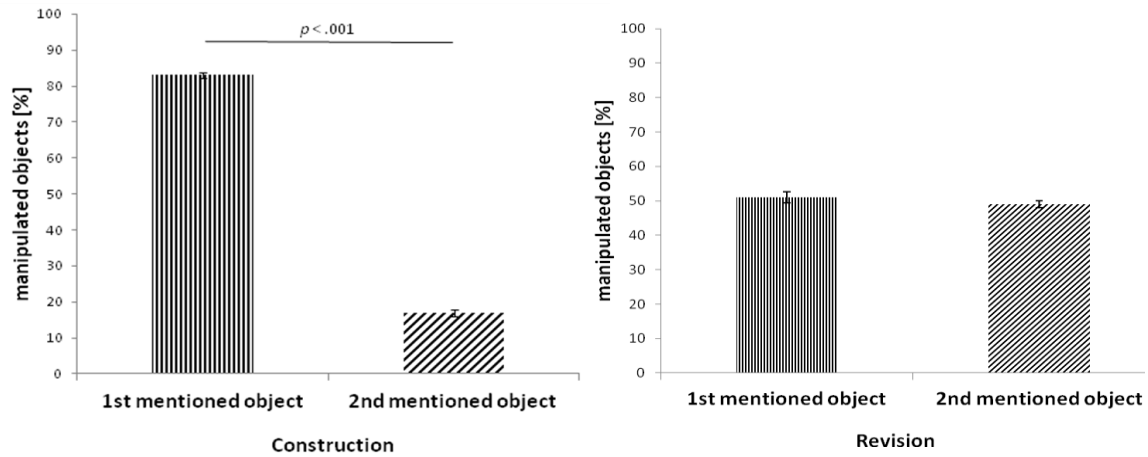


Figure 2. First mentioned objects of relevant spatial information were manipulated first during construction, reflecting an order effect. This order effect was not present during revision. Error bars show standard errors.

General discussion

We investigated what processes guide belief revision in reasoning with spatial mental models. We focused on the question whether revision of initial models is guided by vital steps remembered from the construction phase or whether they solely rely on spatial information provided by inconsistent facts. Further, we examined principles applied during the construction of spatial mental models as compared to the variation of these models.

Our results suggest that when forced to revise initial beliefs about the arrangement of objects in space in the light of contradicting facts, reasoners integrate new pieces of information by modifying fully integrated initial mental models. Variation processes are not influenced by information used during the construction phase. This is in accordance with the notion of informational economy and provides evidence that manipulating mental models is more parsimonious than storing initial descriptions and vital steps used to construct these models (Experiment 1).

Construction processes followed the order of objects as they were mentioned in the relevant spatial description, i.e. there was a clear order effect. This order effect did not occur during variation. This implies that different principles are applied during the construction and the variation phase, respectively, suggesting distinct underlying cognitive mechanisms, accordingly (Experiment 2).

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Chapter 3

Spatial Belief Revision⁴

⁴ This work was published in a slightly different form in: Knauff, M., Bucher, L., Krumnack, A., & Nejasmic, J. (2013). Spatial belief revision. *Journal of Cognitive Psychology*, 25(2), 147-156.

Abstract

Belief revision is the process of changing one's beliefs when a newly acquired fact contradicts the existing belief set. Psychological research on belief revision mostly used conditional reasoning problems in which an inconsistency arises between a fact, contradicting a valid conclusion, and the conditional and categorical premises. In this paper, we present a new experimental paradigm in which we explore how people change their mind about the location of objects in space. The participants received statements that described the spatial relations between a set of objects. From these premises they drew a conclusion which then, in the next step, was contradicted by a new, irrefutable fact. The participants' task was to decide which of the objects to relocate and which one to leave at its initial position. We hypothesised that this spatial revision process is based on mental models and is affected by the functional asymmetry between reference objects (RO) and the located objects (LO) of spatial relations. The results from two experiments corroborate this hypothesis. We found that individuals have a strong preference to relocate the LO of the inconsistent fact, but avoid relocating the RO. This is a novel finding and opens up new avenues of research on how humans mentally revise their beliefs about spatial relations between entities in the world.

Introduction

To understand how people change their opinion over time or in the light of new information that does not agree with their current belief is one of the most fascinating questions of psychology. In daily life, the underlying processes are highly complex and affected by several cognitive, emotional, motivational, and social factors (Kyburg, 1983; Gärdenfors, 1988; Gardner, 2006). Given this complex interplay of many factors, one might think that it is quite unsatisfying if cognitive psychologists select just one of these factors, sometimes even one of minor importance, and then squeeze it into an experimental paradigm, that often seems to be very far away from how people make decisions in daily life. However, cognitive psychologists still adopt this approach for many reasons and indeed - by using this approach - were quite successful in understanding some aspects of

human belief revision. This research almost exclusively uses an experimental paradigm in which participants are confronted with conditional sentences (premises) that posit that if Proposition A is true then Proposition B is true. The work in this paradigm shows that belief revision is effected by many factors, including asymmetries between particular facts and general laws (Revlis, Lipkin, & Hayes, 1971), conditional and categorical premises (Elio & Pelletier, 1997; Dieussaert, Schaeken, De Neys, & d'Ydewalle, 2000; Girotto, Johnson-Laird, Legrenzi, & Sonino, 2000; Revlin, Cate, & Rouss, 2001), major and minor premises (Politzer & Carles, 2001), and reliable and unreliable information sources (Wolf, Rieger, & Knauff, 2012).

In the present paper, we seek to investigate human belief revision within an even more basic experimental paradigm. Our motivation is to pinpoint some of the most essential revision processes by using a particularly simple task that is not affected by people's prior knowledge, preexisting beliefs, or long-term convictions, etc. Another intention is that we do not want to put too much "logic" into our problems. The reason is that reasoning with conditional statements itself is a highly complex research field and that we are still far away from understanding the underlying cognitive processes (Oberauer, 2006; Byrne & Johnson-Laird, 2009; Oaksford & Chater, 2010).

For this reason, we developed a spatial belief revision paradigm in which participants receive information about the location of objects in space but then have to revise their initial assumptions in the light of new information. First, the participants received a premise that described the spatial relation between two objects, e.g., "A is to the left of B". Then they received a second premise that described the spatial relation of one of these objects to a third object, e.g., "B is to the left of C". From these two premises the participants inferred that the three objects are in the arrangement A-B-C. However, they were then confronted with an additional statement, e.g., "A is to the right of C". This is the critical point in time where the participants in our experiments had to realise (and they usually did) that something must be wrong with their initial assumption about the layout of the three objects. Not all three statements can be true at the same time because the third statement contradicts the logical inference from the first two premises.

One option would be to simply ignore the third statement. But that was forbidden in our experiments because the fact has been defined as indisputably true. The only option is to decide which one of the first two premises may be abandoned.

If the first premise is discarded this results in the arrangement B–C–A, if the second premise is discarded this results in the arrangement C–A–B. In other words, in the arrangements B – C – A, the first statement is rejected, but the second (and third) is retained, whereas in C–A–B the second statement is rejected, but the first (and the third) statement is kept. The general structure of the problems is as follows:

| | |
|---|------------------------|
| Premise 1: | A is to the left of B |
| Premise 2: | B is to the left of C |
| Initial model: | A–B–C |
| Contradictory fact: | A is to the right of C |
| Revision alternative 1 [discard P1, retain P2]: | B–C–A |
| Revision alternative 2 [retain P1, discard P2]: | C–A–B |

The two revision strategies lead to two new spatial arrangements which are illustrated in figure 1. In the first revision strategy (left diagram in figure 1), for instance, individuals mentally move the first object (A) in the array from the leftmost to the rightmost position in the array. In the second revision strategy (right diagram in figure 1), individuals move the last object (C) in the array from the rightmost to the leftmost position in the array. Do people prefer to relocate Object A or Object C? Which of the two revised layouts (in figure 1) will be produced more often?

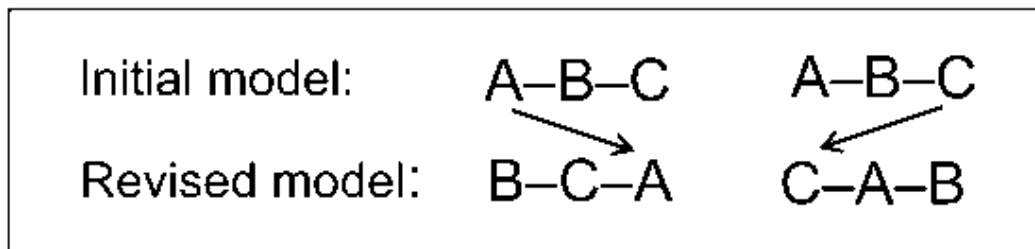


Figure 1. Two revision strategies for the contradictory fact: “A right of C.” Left: LO-relocation; individuals mentally pick the first object (the LO of the contradictory fact) in the array and move it to the end of the array. Right: RO-relocation; individuals choose the last object (the RO of the contradictory fact) in the array and move it to the first position in the array. In both versions, the middle term B connecting the two premises remains untouched.

The following studies are based on three general assumptions:

(1) Spatial reasoning relies on mental models. A mental model is a unified representation of what is true if the premises are true. Spatial relations in such models are not represented explicitly in a propositional format. Rather they are inherent in the model and thus can be (and must be) “read off” from the model by mental inspection processes.

(2) Spatial belief revision relies on the revision of mental models. People revise a model if newly available information is inconsistent with the current model (and the new information must be taken for granted). The revision process relies on local transformations in which tokens in the model are moved to new positions. If not all available information can be true at the same time, people “decide” which of the information to retain and which one to discard.

(3) The model revision process is sensitive to the functional asymmetry between the reference object (RO) and the located object (LO). For instance, in the statement “A is to the left of C”, the C is the RO and the A the object that is located in relation to the RO. The distinction has been made by several psychologists and linguists (Miller & Johnson-Laird, 1976; Talmy, 1983; Landau & Jackendoff, 1993).

The first assumption (that spatial reasoning relies on mental models) represents our general theoretical framework, the mental model theory of reasoning (Johnson-Laird, 1983, 2006; Johnson-Laird & Byrne, 1991). The theory is supported by many experimental findings in the area of relational reasoning. These studies have shown that people construct mental models from spatial and temporal relations and that reasoning with multiple spatial mental models is harder than reasoning with a single model (Schaeken, Johnson-Laird, & d'Ydewalle, 1996; Carreiras & Santamaria, 1997; Schaeken & Johnson-Laird, 2000; Boudreau & Pigeau, 2001). Reasoning also gets harder if the premises are more difficult to integrate into a unified mental model (Ehrlich & Johnson-Laird, 1982; Byrne & Johnson-Laird, 1989; Nejasmic, Krumnack, Bucher, & Knauff, 2011) or if the problem evokes irrelevant visual images (Knauff & Johnson-Laird, 2002). Other theories of relational inference cannot readily explain these findings (Johnson-Laird & Byrne, 1991; Carreiras & Santamaria, 1997; Roberts, 2000; Goodwin & Johnson-Laird, 2005; Juhos, Quelhas, & Johnson-Laird, 2012; Knauff, 2009, 2013).

The second assumption (that spatial belief revision relies on the revision of mental models) creates a new link between the model theory and spatial belief revision. Models should not be confused with beliefs, but models give rise to beliefs (see General discussion). How people revise models is still one of the main research questions within model theory and intimately linked to the variation (and validation) of mental models. Recent empirical studies suggest that people do not create alternative models by entering a loop of model construction and model inspection (Bucher, Krumnack, Nejasmic, & Knauff, 2011; Krumnack, Bucher, Nejasmic, & Knauff, 2011; Bucher & Nejasmic, 2012). Rather, they start from the preferred model and alter this model by local transformations (Ragni, Knauff, & Nebel, 2005; Rauh et al., 2005). Annotations are used to maintain those aspects of the premise information that are necessary to vary the model (Vandierendonck, Dierckx, & De Vooght, 2004).

In the studies reported later, we focus on the third assumption (that the model revision process is sensitive to the functional asymmetry between RO and LO). In principle, it is logically possible that spatial relations could be mentally represented as

propositions of the form $r(A, B)$, where A and B are the objects to be located (Landau & Jackendoff, 1993). In human spatial cognition, however, the dominant way to represent spatial relations between objects is asymmetrical (Miller & Johnson-Laird, 1976; Landau & Jackendoff, 1993). Usually, one object is considered to be the reference object (RO), and the other is the located object (LO). Some authors refer to the located object as figure and the reference object as ground; others distinguish between locatum and relatum (Talmy, 1983; Landau & Jackendoff, 1993). The common idea of all these theories is that a spatial relation refers to the position of a particular object in focus relative to another object or area (Tenbrink, Andonova, & Coventry, 2011).

The RO-LO asymmetry is also important for the present studies because we assume that the asymmetry also affects the revision of spatial mental models. In the contradictory fact of our example “A is to the right of C” the A is the LO and the C is the RO. Moving the middle term B does not solve the problem.

This leads to the following hypothesis:

Individuals prefer to relocate the object which is the LO of the contradictory fact, because the LO is considered to be more flexible and less stationary. The RO usually remains at its initial position, as it is treated as a kind of “landmark” which should not be moved (the middle term is never relocated.)

Henceforth, we refer to this as LO-relocation or LO hypothesis; the alternative hypothesis we refer to as RO-relocation or RO hypothesis. We present two experiments that tested these hypotheses. In the first experiment, the participants had to solve the revision problems just mentally by envisaging how the objects in the initial model must be rearranged. In the second experiment, the participants had to solve the problem manually by locating and relocating actual physical objects in a simple blocks world environment.

Experiment 1

Method

Participants. We individually tested 23 students from the University of Giessen (three male; age: $M = 22.22$, $SD = 2.45$, two psychology students). They gave written informed consent and were paid for their participation.

Materials and procedure. The experiment (with-in-subjects design) consisted of 32 problems (and four practice trials) each of which consisted of three statements. As objects we used fruits (apple, kiwi, mango, peach) and tools (wrench, hammer, pliers, and screwdriver) because for these objects no typical arrangements exist (Dutke, 1993). In half of the problems, the first premise used the “left of” relation and the “right of” relation in the second premise, whereas in the other half it was reversed. The other half of problems used the same relations in all sentences. The contradictory fact also used either “left of” or the “right of” relation. At the beginning of each problem the two premises P1 (e.g., “the apple is to the left of the peach”) and P2 (e.g., “the peach is to the left of the kiwi”) were presented one after the other, centred on the screen by the participants’ own speed. Then two “models” were presented from which one was in agreement with the two premises (apple–peach–kiwi) and the other was not possible if the premises were taken for granted (kiwi–peach–apple).

This was done to guarantee that the people have the “correct” model (e.g., apple–peach–kiwi) in mind, before they entered the revision phase, and in fact more than 95% ($M = 95.65$, $SD = 1.30$) of the models were correctly selected by the participants. The few problems in which they chose the “wrong” model (e.g., kiwi–peach–apple) were eliminated from the further analysis.

In the next step, the contradictory fact (e.g., “the apple is to the right of the kiwi”) was presented on the screen and the participants decided by a keypress whether this fact was in agreement with the initial statements (we explicitly told our participants that the contradictory fact is irrefutably true). In more than 90% ($M = 90.49$, $SD = 9.01$) of the problems the participants made the correct decision and the few invalid decisions were eliminated from the further analysis.

Then the essential decision of the experiment followed: Two alternative revised models were presented on the screen, from which one followed the LO-hypothesis (peach–kiwi–apple), whereas the other followed the RO-hypothesis (kiwi–apple–peach). The position of objects and tools were counterbalanced over the group of problems and participants.

Results and discussion

Figure 2 presents the percentages of responses corresponding to the two revision alternatives. Apparently, participants had a strong tendency to relocate the object that served as the LO of the contradictory fact ($M = 87\%$, $SD = 3.44$), whereas they only very seldom relocated the RO ($M = 13\%$, $SD = 3.44$). This result is statistically significant, Wilcoxon test, $z = -4.22$, $p < .001$, and corroborates the LO-hypothesis, but is contrary to the RO-hypothesis. Our findings have some theoretically interesting implications.

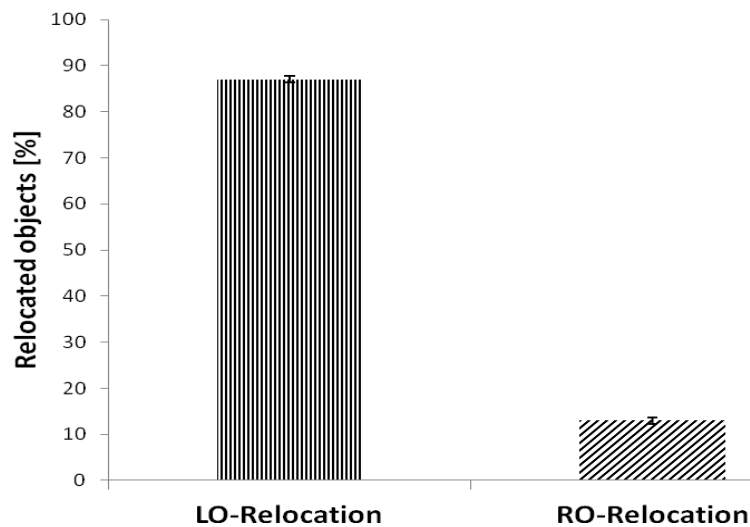


Figure 2. Relative frequency (in%) of model selections following the LO- and RO-relocation hypothesis (Experiment 1).

In particular, the results are difficult to explain based on purely propositional representations of spatial relations. If relations were mentally represented as propositions of the form $r(A,B)$, where A and B are the objects to be located, we would not expect an asymmetry between LO and RO. If, however, people construct and revise mental models

of the premises this might account for the asymmetrical semantic roles the objects play during the processing of spatial relational expressions. This assumption is supported by several experimental findings. Logan (1994, 1995) showed that if individuals are asked to verify spatial relations in a diagram they shift attention from the RO of the statement to the region where the LO is expected (see also Oberauer & Wilhelm, 2000). Hörnig, Oberauer, and Weidenfeld (2005) studied the integration of new premise information into an already existing model and reported that reasoners integrate the LO of a relation faster if the RO of the premise was already part of the existing model.

In the present experiment we were able to show that such semantic directionality effects also play an important role during model revision. The effects do not only influence how a model is constructed, as previous results suggest. Semantic directionality and the asymmetry between RO and LO obviously also have an effect when people already have constructed a model but then have to alter this model because they receive new information that does not concur with the present model. In the next experiment we test how universal such revision principles are. In particular, we wanted to explore whether the same preference for LO relation exists, if people are asked to manually move actual physical objects.

Experiment 2

What happens if people must revise an arrangement of actual physical objects? In the previous experiment, the individuals had to mentally envisage an arrangement of objects and how the objects must be relocated to account for the new fact. In the present experiment, the participants were instructed to place real physical objects on a table and then to move these objects with their hands to revise the initial arrangement. We predicted that the LO-relocation principle is not limited to the mental revision process, but also guides revisions that a person must manually execute.

Method

Participants. We tested a new sample of 22 students from the University of Giessen (five male; age: $M = 22.59$; $SD = 3.16$ five psychology students). They gave written informed consent and were paid for their participation.

Materials and procedure. The participants were sitting at a table on which they found (on a plate) a red, a blue, a green, and a yellow wooden block with 2.5 side length. The blocks were located in front of a 19" computer monitor on which the statements (Premise 1, Premise 2, incontrovertible fact) were presented as a sequence of Power-Point slides at the participants' own speed (the experimenter pressed a key to proceed through the experiment).

Again, the experiment (within-subjects design) consisted of 32 problems (and four practice trials) each of which consisted of three sentences. The first premise described the spatial relation between two coloured blocks, e.g., "The red block is to the left of the green block". The participant now manually positioned the two blocks on the table. Then the second premise described the spatial relation between one of these block to a third block, e.g., "The blue block is to the right of the green block". The participant now positioned the third block on the table. Now the incontrovertible fact was presented. It described the relation between two blocks that contradicted the participant's layout of objects, e.g., "The red block is to the right of the green block". Now the participants were instructed to pick one block of their own choice and to manually relocate this block to gain an arrangement that is consistent with the incontrovertible fact. The participants were free in their choice, as long as they just picked only one of the objects.

After each problem, the blocks were put back onto the plate by the experimenter. Again the used spatial relations ("left of", "right of") appeared equally often in the two premises and the contradictory fact. The participants' actions (hand and block movements) were videotaped by a video camera that was positioned on a stand to the right of the participant.

Results and discussion

Our analysis started with the analysis of video-taped revision processes. In this analysis, for each problem the block repositioning (movement of a block to another position) was classified as either following the LO-hypothesis or the RO-hypothesis, respectively. In figure 1 and a given fact “A the right of C”, for instance, a block repositioning concurred with the LO-hypothesis if the participant moved the first block in the array to the last position; a block repositioning counted as RO-relocation if the participants moved the last object in the array to the first position.

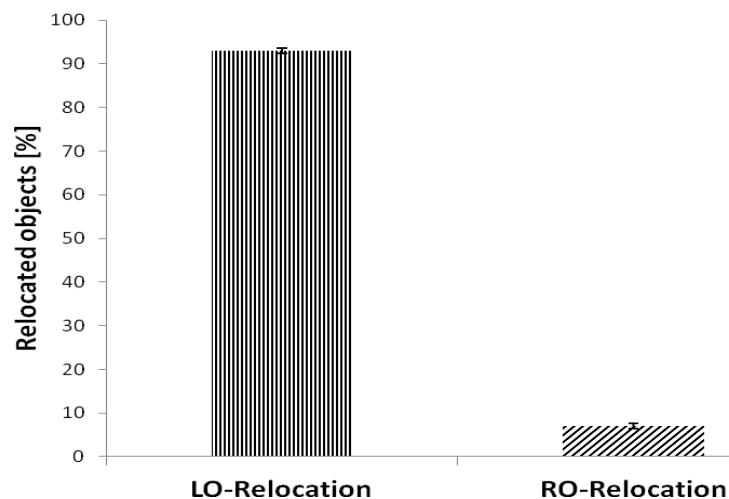


Figure 3. Relative frequency (in%) of block relocations following the LO- and RO-relocation hypothesis (Experiment 2).

Figure 3 presents the percentages of block relocations following the two revision alternatives. Again, participants had a strong tendency to relocate the object that served as the LO in the contradictory fact ($M = 93\%$, $SD = 2.57$), whereas they only very seldom relocated the RO of the inconsistent fact ($M = 7\%$, $SD = 2.57$). This result is statistically significant, Wilcoxon test, $z = -4.27$, $p < .001$, and shows that the participants again favoured to revise the arrangement according to the LO-relocation principle.

In fact, it seems as if people use the same revision principle no matter whether they solve the entire task just in their head or in a real physical environment. We are aware that this is just the first finding in this direction and that further experiments are needed to

clarify how universal the LO-relocation principle is in real spaces. For example, it is possible that the physical revision of spatial arrangements differs on different spatial scales, ranging from small-scale space that we can reach by our hands to large-scale space that requires locomotion. It is also possible that the revision process is influenced by aspects of the body. For instance, in two recent experiments, we found that people avoid moving large and heavy objects and this can overwrite the LO-relocation principle (Nejasmic, Bucher, & Knauff, 2013).

However, we did not design the experiment to answer such questions of embodiment (Barsalou, 2008) but to show that the LO principle is more universal than one might think. LO-relocation is the guiding principle if the problem is just solved mentally and it also drives the active manipulation of objects in real spatial arrangements.

General discussion

How humans revise their beliefs is one of the most challenging questions of psychology, but has so far been investigated just to a very limited extent. Most of the available studies are from the domain of conditional reasoning and have shown that a particular fact is more often abandoned than a general law (e.g., Revlis et al., 1971), people sometimes prefer to revise their belief in the conditional (Elio & Pelletier, 1997), whereas in other settings they tend to revise the categorical premise (Dieussaert et al., 2000; Girotto et al., 2000; Revlin et al., 2001). Some researchers ascribe such asymmetries to the linguistic form of the conditional (e.g., Elio & Pelletier, 1997), whereas others argue that the preference is caused by the differences between major and minor premises (e.g., Politzer & Carles, 2001). Yet others have shown that the preferences are strongly affected by the trustworthiness of the information sources (Wolf et al., 2012) and that people have difficulties to reconsider their prior beliefs (Knauff, Budeck, Wolf, & Hamburger, 2010). The intention of the present paper was to extend the cognitive research on human belief revision to the area of relational reasoning.

Our main motivation was that (1) relational inferences are probably the most frequently used form of reasoning in our daily life (Goodwin & Johnson-Laird, 2005;

Knauff, 2013), (2) reasoning with relations is often easier than reasoning with conditionals (Johnson-Laird & Byrne, 1991; Knauff, 2007), (3) relations are ubiquitous in many high-order cognitive processes, such as reasoning, categorisation, planning, and language (Halford, Wilson, & Phillips, 2010), and (4) that relations and inferences on them give rise to people's choices, preferences, and attitudes (Lichtenstein & Slovic, 2006). A second motivation for the present research is that relations are intimately linked to space and that space is one of the most fundamental dimensions of our physical and psychological reality. Crucially, many spatial cognition researchers have argued that the mental space is not geometrically organised, but rather a relational space in which objects are located in relation to other objects (Gattis, 2001; Knauff, 1999). Given this prominence of space in our mind, we believe that it is sensible to develop a specific paradigm that allows us to study how people deal with conflicts in spatial representations and how they solve these inconsistencies in order to gain a consistent mental representation about the relative location of objects in space.

Our main finding is that the cognitive processes underlying such revisions are guided by the construction and variation of spatial mental models and the differences between reference object and located object in the problem description. We are, however, aware that our account is by no means complete. One problem is that our results might have to do with effects of the direction of written language (from left to right versus right to left; e.g., Spalek & Hammad, 2005; Jahn, Knauff, & Johnson-Laird, 2007) and that we used the simplest sort of relational inferences with just two premises and three objects. Future research must clarify whether or not the LO-relocation principle is also so dominant in more complex reasoning problems. Another problem is that our results might have to do with one-by-one presentation of the premises and the contradictory fact. It is possible that this has triggered certain revision strategies and that individuals would use different strategies if all information would be available at the same time. Future experiments will help us to further define the boundary conditions and limitations of our present account and will also help us to identify further spatial belief revision strategies. Another difficulty of the paper is that we are (despite better knowledge) quite careless in the use of the terms

“belief” and “model”. In fact, we often used the terms interchangeably, although this is theoretically problematic.

A belief is usually defined as a propositional attitude, which implies the concept of intentionality. It requires a subject, who is the believer, and an object of belief, the proposition (Schwitzgebel, 2011). A proposition is a mental entity that represents meaning in a language-like code and has a truth value “true” or “false”. Although propositional representations should not be identified with linguistic representations, they are language-like in the sense that they comprise abstract symbols as a language does (e.g., Anderson, 1993). As such, beliefs are not the same as models. Moreover, a specific model can be described by different propositions, and more than one model can be compatible with the same set of propositions.

Strictly speaking, model revision is therefore not the same as belief revision and what we explore in the paper is primarily model revision rather than belief revision. However, this issue is very subtle, and we do not make this distinction in this short paper. Overall, however, we believe, we could show that people are very good in detecting inconsistencies in a set of statements describing the spatial relations between objects (cf. Johnson-Laird, Girotto, & Legrenzi, 2004). They notice that a new fact does not concur with a set of forgoing statements and thus are also willing to change their putative model of the problem description. If, in a second step, they have to decide how to revise the initial model, they tend to leave the RO of the new fact where it already is and relocate the LO. The reason is the asymmetry between the RO and LO, which is well known from many studies in the area of spatial cognition research (Talmy, 1983; Herskovits, 1986; Hayward & Tarr, 1995; Jackendoff & Landau, 1995). Since the LO is considered to be the more flexible element in a spatial description, it is easier to move this object mentally to another position within a model than the RO, which typically is viewed as a stationary “landmark” which should be left at its initial position (e.g., Herskovits, 1986; Hayward & Tarr, 1995).

This account agrees with the mental model theory, in which people reason by constructing, inspecting, and varying spatial mental models. As we have shown earlier, the

model variation process in this theory follows the principle of minimal changes (Harman, 1986; Bucher et al., 2011; Krumnack et al., 2011) which says that reasoners try to keep as much as possible of a model unchanged and only vary what is absolutely necessary in order to gain a consistent mental representation of the problem scenario. The LO-relocation principle in this paper agrees with this principle of minimal changes. Further experiments are needed to explore this topic more thoroughly.

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Chapter 4

Relocating multiple objects during belief revision⁵

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Abstract

Reasoners need to revise their beliefs about the state of the world when confronted with contradicting evidence. In the spatial context, belief revision is assumed to be accomplished by variation of initially constructed spatial mental models. The revision process includes decisions about which part of a model to retain and which one to modify. Usually, there are several alternatives for model variation that re-establish consistency within belief sets. Frequently, these alternatives are logically equivalent. Nevertheless, human reasoners show clear preferences for certain alternatives. The assumption is that the preferences result from the application of principles that are cognitively more economic compared to others. In two experiments, we investigate how the number of objects involved in model variation processes affects preferences in model variations during spatial belief revision. We discuss whether the results can be explained in terms of cognitive economy.

Introduction

Multiple sources provide us with information about the state of the world. Sources differ in many ways, for instance concerning reliability, familiarity, and trustworthiness. Additionally, the context, information is concerned with, is more or less familiar, information itself more or less plausible, probable, important, and so on. Some pieces of information simply confirm what we already know or believe to know about the world and some increase our knowledge base. However, some conflict with what we believe. That entails that these pieces of information are not addable to sets of already existing beliefs in a monotonic way but cause the need for giving up existing beliefs to re-establish consistency within these sets (Gärdenfors, 1992). Belief sets need to be *updated* when reliable information indicate that the world has changed. They need *revision*, when information surface which reliably indicate that some of our existing beliefs are not maintainable because they are obviously not true (Gärdenfors, 1992; Elio & Pellitier, 1997; Wolf & Knauff, 2008). Here is an example:

- (5) Filling station Bakery
Supermarket
- or
- (6) Bakery
Fillingstation
Supermarket

Arrangements (5) and (6) are modifications of the initial arrangement. Arrangement (5) is obtained by relocation of the “Supermarket” within the initial arrangement; it preserves the information conveyed by statement (1). Arrangement (6) is obtained by relocation of the “filling station”; it preserves information from statement (2). Both arrangements involve the same amount of changes in terms of relocated objects (one, respectively). Also, the same amount of information from the descriptions is preserved/retracted in both alternatives. Thus, the amount of changes does not help with the choice of which assumption about the arrangement of the buildings should be preferred over the other. From a logical point of view, arrangements (5) and (6) are equivalent variations of the initial arrangement. Thus, logic does not help with the choice of how to modify the initial arrangement, either. Both, the amount of changes and logic indeed would leave reasoners undecided or confused. However, studies that looked at spatial reasoning suggest that human reasoners indeed clearly prefer certain alternatives over others (Knauff, Rauh, & Schlieder, 1995; Knauff, Rauh, Schlieder, & Strube, 1998; Ragni, Knauff, & Nebel, 2005; Jahn, Knauff, & Johnson-Laird, 2007; Krumnack, Bucher Nejasmic, & Knauff, 2010; Krumnack, Bucher, Nejasmic, Nebel, & Knauff, 2011b).

The present paper is concerned with the factors that lead to preferences in spatial reasoning during the revision of spatial beliefs. The general questions are: how are spatial relations processed during revision? And, what guides the revision process? Subsequently to summarizing theoretical assumptions and empirical findings about spatial relational reasoning and spatial belief revision, we present two experiments that investigated revision of spatial beliefs with two-dimensional arrangements of four objects. Alternatives to revise these arrangements differed in the number of objects (one vs. two) involved in the revision process. The specific question was: What role does the number of objects,

relocated in order to modify an initial arrangement, play during revision? Does it provide a guiding factor in the course of revision in the sense that reasoners prefer to keep the changes in terms of relocated objects little? In that case, reasoners should prefer relocating single and avoid relocating multiple objects.

Relational reasoning with spatial mental models

Many studies show that during reasoning with spatial relations, the objects and relations are represented in spatial mental models. Relational reasoning is describable in distinct phases: in the first phase, reasoners *construct* spatial mental models that reflect the information provided by the premises. This model allows for the *inspection* in search of information that is not explicitly given in the premises. Inspection phase is followed by a *variation* phase. During this phase, reasoners vary preferred mental models in order to find alternative interpretations of the premises. However, this model variation takes place only if it is required by the specific problem. If this is not the case people only rarely search for counterexamples that refute a putative conclusion. This often leads them into errors and logically invalid inferences (Knauff et al., 1995; Jahn et al., 2007). Vast empirical evidence corroborates the notion that construction and inspection of spatial mental models provide the basis of relational reasoning (Maybery, Bain, & Halford, 1986; Johnson-Laird & Byrne, 1991; Knauff et al., 1995; Schaeken, Johnson-Laird, & Ydewalle, 1996a; Carreiras & Santamaria, 1997; Vandierendonck & De Vooght, 1997; Schaeken, Girotto, & Johnson-Laird, 1998; Schaeken & Johnson-Laird, 2000; Knauff & Johnson-Laird, 2002; Rauh, et al., 2005; Bucher, Krumanck, Nejasmic, & Knauff, 2011).

The question, the present work focuses on is how reasoners deal with spatial information that partly conflicts with information they have received beforehand and that run counter their beliefs about the spatial arrangements of objects. To take contradicting information into account with the aim to re-establish consistency within a certain belief set, reasoners need to detect inconsistencies between a former description and a new piece of information. Johnson-Laird, Girotto, & Legrenzi (2004a) and Johnson-Laird, Legrenzi, & Girotto (2004b) describe the ability of reasoners to detect inconsistencies in terms of model

inspection. They conclude that, in general, reasoners detect conflicts quite reliably (Johnson-Laird et al., 2004a; Johnson-Laird et al., 2004b). Inconsistency detection implies the detection of a conflict between previously given information with a new piece of information. Given the new piece of information is an incontrovertible fact, reasoners need to decide which piece(s) of information, initial beliefs are based upon conflict with this fact. Frequently, there are multiple alternatives for re-establishing consistency within belief sets and logic does not provide criteria for the decision which information to retract and which to retain in the course of revision.

Variation of spatial mental models during revision

It is assumed that reasoners base their revisions of beliefs about the relations of objects in space on a variation of initially constructed spatial models (Knauff et al., 1995; Knauff et al., 1998; Ragni et al., 2005; Rauh et al., 2005; Jahn et al., 2007; Krumnack et al., 2010; Krumnack, Bucher, Nejasmic, & Knauff, 2011; Bucher et al., 2011). The revision phase is deemed as a distinct phase, following construction and subsequent inspection (implicating inconsistency detection) of a spatial mental model (Bucher et al., 2011).

The process of model variation itself has been shown to be guided by specific factors. With verbal descriptions expressed in a binary relations with $r(X,Y)$, it has been shown that it relies on cues provided by conflicting information (Bucher et al., 2011; Krumnack et al., 2011a). A binary relation holds semantic cues that result from the semantic distinction of X as the “to-be-located object” (LO) in contrast to Y as the “reference object” (RO). The asymmetry of the two arguments (LO, RO) specifies the location of the LO relative to the known location of the RO (Miller & Johnson-Laird, 1976). Several empirical findings corroborate this assumption, for instance, findings in studies on the integration of new spatial information provided by binary relations into already existing spatial models (Oberauer & Wilhelm, 2000; Hörnig, Oberauer, & Weidenfeld, 2005; Oberauer, Hörnig, Weidenfeld, & Wilhelm, 2005; Nejasmic, Krumnack, Bucher, & Knauff, 2011). In his theory, Logan (1994, 1995) proposes that

attention is turned to a certain region by linguistic cues provided by these relations (Logan, 1994; 1995). Attention moves from a statement's RO to the region the LO can be expected. The findings converge to that effect that reasoners consider an RO's position as fixed while the LO is flexible and locatable relative to the RO's position.

For the variations of horizontal linear arrangements, the following finding concerning reasoners' preferences is characteristic (Krumack et al., 2010; Bucher et al., 2011; Krumnack et al., 2011a):

| | |
|-------------------------------|--|
| Initial arrangement | A B C |
| Contrafact | C is left of A, <i>with C as the relation's LO</i> |
| Preferred varied arrangement: | C A B |

Note that the logical equivalent (non-preferred) alternative for variation of the initial arrangement by relocating the contrafact's RO (here: A) results in the revised arrangement:

B C A.

Basically, the position of objects as rearranged during the variation process of spatial belief revision is guided by information provided by the contrafact.

The number of objects and relational complexity

Here we present two experiments which investigated revision processes with relations more complex compared to relations of three objects. Verbal descriptions were presented that described the arrangements of four objects in a two-dimensional layout, such that the first three objects were aligned horizontally and the fourth object was related to one of the outer positioned objects of the horizontal arrangement. Participants' task was to construct the arrangement from the description and present the solution either by drawing (experiment 1) or by choosing the correct arrangement from two presented

arrangements (experiment 2). Subsequently, participants were asked to judge whether a statement (binary relation about the two objects positioned at the outmost locations of the horizontal arrangement) that was introduced as “fact” about the arrangement at hand was consistent with previous information or not. In case of inconsistency detections, participants were asked to revise their assumptions about the relations of objects among each other by taking into account the fact’s spatial information. In experiment 1, participants were asked to sketch relations of the objects by drawing. In experiment 2, they were asked to choose between two alternative arrangements. Our hypotheses concerning fundamentals underlying the revision process are:

- revision is accomplished by *variations* of initial arrangements.
- variations incorporate the fact’s information while as much of the initial information as possible is preserved.

Experiment 1 tested these assumptions in a situation allowing participants to sketch the objects’ relations unconfined and to generate their drawings freely. Given, reasoners vary initial models, the following factors might influence variation: semantic cues provided by contrafactual information or the number of objects that need to be re-located in order to regain consistency. When the spatial information provided by contrafactual statements is vital, rather than factors adherent to arrangements, the basic principle applied in variation should rely on semantic cues provided by the contrafact. The application of this principle would lead to the following observation:

- model variation is preferably based on the relocation of the fact’s LO relative to its RO as compared to the relocation of the fact’s RO relative to its LO.

When the number of objects relocated during revision might provide a guiding factor for variation, in the sense that reasoners prefer keeping the changes (number of relocated objects) little, this would lead to the following observation:

- model variation preferably involves the relocation of one object than of two objects.

Reasoners' preferences were examined in both experiments. Additionally, experiment 2 intended to provide a closer look at processing times related to variation. The assumption is:

- variation processes that involve multiple objects take longer than of single objects.

The number of items, chunks, or units of information has been suggested to increase complexity (Miller, 1956). With relational processing the pivotal role for determining complexity is played by relational complexity (Halford, Wilson, & Phillips, 1998; Phillips & Niki, 2002). Accordingly, increased complexity of ternary or quaternary relations compared to binary relations results from interactions of the components adherent to a problem, e.g. the number of objects, relations etc. The more complex a problem the more processing capacity is needed or, differently phrased, the more cognitive resources are demanded. Processing capacity means, the amount of information stored to be processed later (Hitch, 1980). It is often referred to as "working memory capacity" with the working memory maintaining the information which is processed by the central executive. Allocation of cognitive resources and thus the demand for processing a certain task can be measured, e.g. by the decrement of performance of more difficult tasks that require more resources compared to less difficult tasks that require less (Navon & Gopher, 1980; Halford et al., 1998). Solutions of or decisions on problems should take longer with increased demands on cognitive resources as caused by increased complexity. The

There was a blank slide presented for 2s before the next problem was shown. 32 experimental problems were presented, preceded by four practice problems (not analyzed).

Descriptions were provided using Microsoft PowerPoint (Version 2007) running in the windows environment XP on a standard personal computer. PowerPoint slides were presented on a big screen via video projector. Participants used a pencil to individually write down the constructed arrangements into specially prepared booklets.

Participants were instructed to draw the object arrangement according to the description. The instruction included the hint that they could not be entirely sure whether the information about the object arrangement was true. And that they would be presented with a fourth statement which would provide information about the arrangement at hand that has to be taken as a fact and being incontrovertible as such. Participants' task was to follow the prompts, i.e. sketching the object arrangements into the booklet and turning the page, when instructed by the presented slides likewise.

Drawings of each participant were analyzed after the experimental session. Percentage values for correctly drawn arrangements were calculated. Of special interest were the drawings, generated after the information of the fact was taken into account. There were two alternatives for revising the initial arrangement in order to take into account the fact information while preserving as much of the initially provided information (from the premises): The alternatives can be described as follows:

1. The initial arrangement is revised by relocation of the fact's LO;
2. The initial arrangement is revised by relocation of the fact's RO

In half of the problems, the LO, in the other half the RO was attached by the fourth object. The question was whether the object attached to either the LO or the RO would affect the choice of a certain revision alternative. From a formal logical point of view, all alternatives were equivalent.

Results and discussion

Mean percentage rate of correctly drawn arrangements in the first step (construction phase) was 85% ($SD = 17.31$). Erroneous trials were excluded from further analysis. Mean percentage rate of correctly drawn arrangements in the second step (revision phase) was 84% ($SD = 20.36$). Erroneous trials were excluded from further analysis.

For the revision phase an ANOVA with the factors object (LO, RO) \times object number (1,2) was conducted. There was a significant main effect of object, $F(1,23) = 130.32$; $p < .001$; $\eta^2 = .850$. Main effect of object number and the interaction were non-significant ($ps > .15$). T-tests revealed that the drawings of revised arrangements were based significantly more often on relocations of LOs ($M = 88\%$, $SD = 16.45$) than of ROs ($M = 12\%$, $SD = 16.45$). See also figure 1.

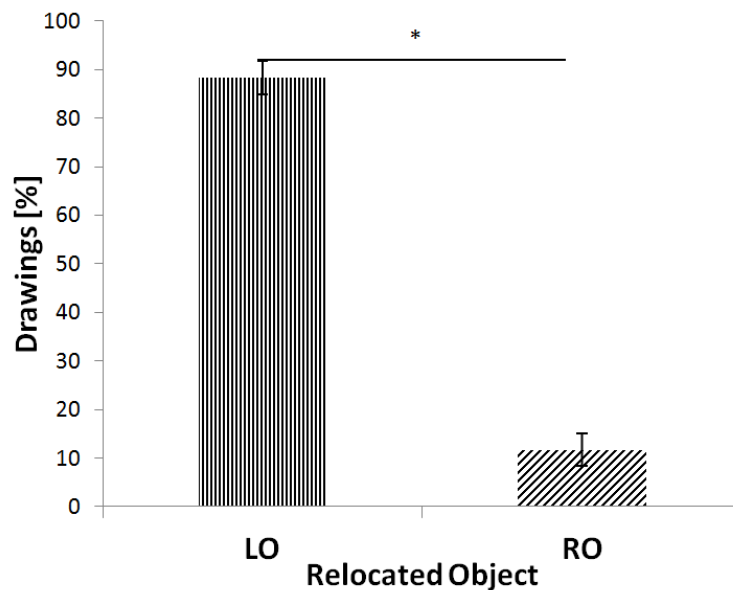


Figure 1. Percentage rates for drawings of revised arrangements based on the relocation of to be located (LO) and reference objects (RO) are depicted. Error bars indicate standard errors.

Results indicate that revision was accomplished by varying initial arrangements and that variations were guided by semantic cues provided by the contra fact. Drawings revealed clearly reasoners' preference for relocating facts' LOs relative to ROs. LOs as single objects (in half of the problems) were comparably often subject to relocation

compared to LOs attached with an additional object (in the other half of the problems). Attached objects were always relocated together with the relocated object, i.e. participants treated the pair of objects as a “chunk”. There was no exception in none of the drawings. This finding implicates that information initially provided during the construction phase was preserved best possible. With experiment 2, we assessed variation processes in terms of cognitive economy in a two-alternative forced-choice task.

Experiment 2: Choosing between spatial arrangements

Method

Participants. Twenty-three participants (9 male; age: $M = 23.22$ $SD = 3.06$) all students (among them 8 students of psychology) from the University of Giessen, gave written informed consent to participation. Participants were tested individually and paid at a rate of 8 Euro per hour.

Materials, procedure, and design. All problems followed a tripartite structure with a layout description, inconsistency detection, and a revision part.

Comparable with experiment 1, in the layout description part, three premises (presented sequentially in a self-paced manner, only one visible on the screen at a time) described a two-dimensional layout of four objects. Objects and relations presented in the descriptions were comparable to those of experiment 1. Subsequently to premise presentation the correct spatial arrangement of the objects and an incorrect arrangement (correct arrangement inverted), see example below, were presented:

Correct arrangement:

Apple Mango Pear

Kiwi

incorrect arrangement:

Pear Mango Apple

Kiwi

Participants were instructed to choose the correct object arrangement (resulting from the description), presented on the left and right side of the computer screen, indicating their choice by pressing a left or right response button with the left or right hand,

accordingly. Left and right locations for correct and incorrect arrangements were counter-balanced across the experiment. The number of correct decisions and corresponding decision times were recorded.

In the following inconsistency detection part a fourth statement (fact) was provided. Consistent (in half of the problems) and inconsistent facts (in the other half) resembled the facts presented in experiment 1. The participants were instructed to decide whether the fact was consistent or inconsistent, indicating their decision by pressing the respective response button (the side of the response-buttons “yes” and “no” were counter-balanced across participants) with the left or right hand, accordingly. Successful inconsistency detection and corresponding detection times were recorded.

The third part, the revision 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 inconsistent fact’s spatial information. They were presented with two object arrangements, on the left and the right side of the computer monitor. Participants were asked to choose that arrangement which matches their assumption, indicating their choice by pressing the left or right response button, respectively.

In fact, both arrangements were consistent with the presented “fact”. However, the arrangements differed with respect to the initial arrangement based on the relocation of the inconsistent fact’s LO or the fact’s RO. Again, as in experiment 1, in half of the problems, the fact’s LO and in the other half the fact’s RO was identical with the object attached by the fourth object in the initial arrangement.

Presentation locations of the arrangements were counter-balanced across the experiment. Revised arrangements chosen and corresponding revision times were recorded.

32 experimental, preceded by 6 practice trials (not analyzed) were presented in a random order. All stimuli were generated and presented using 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

Overall, the participants' performance was very high. The correct arrangements of objects (in the first phase) was chosen in 91% ($SD = 9.76$) of the trials within 3.27s ($SD = 1.04$). Erroneous problems were excluded from further analysis. In the second step (inconsistency detection) the performance was also high. Facts' inconsistency with initial information from the premises was recognized correctly by the participants in 95% ($SD = 8.79$) of all problems and took 3.03 s; ($SD = .88$) on average (erroneous trials were excluded from further analysis).

To examine the principle applied by reasoners during the revision phase (the third phase), ANOVAs with the factors object (LO,RO) \times object number (1,2) were calculated separately for percentage rates and revision times. ANOVA for the percentage rate revealed a main effect of object, $F(1,22) = 34.44$; $p < .001$; $\eta^2 = .610$. The main effect of object number and the interaction were non-significant ($p > .30$). Arrangements revised based on relocations of contra facts' LOs ($M = 70\%$; $SD = 16.68$) were chosen significantly more often compared to ROs ($M = 30\%$; $SD = 16.68$), $t(22) = 5.86$; $p < .001$.

ANOVA for the revision times revealed a marginally significant main effect of object number, $F(1,14) = 3.97$; $p = .066$; $\eta^2 = .221$. The main effect of object and the interaction object \times object number were non-significant ($p > .30$). *T*-tests comparing decision time means for relocating one ($M = 6.21$ s; $SD = 3.41$) compared to two objects ($M = 7.62$ s; $SD = 4.23$) were marginally significantly lower, $t(23) = 2.07$; $p = .051$. Figure 2 provides an overview.

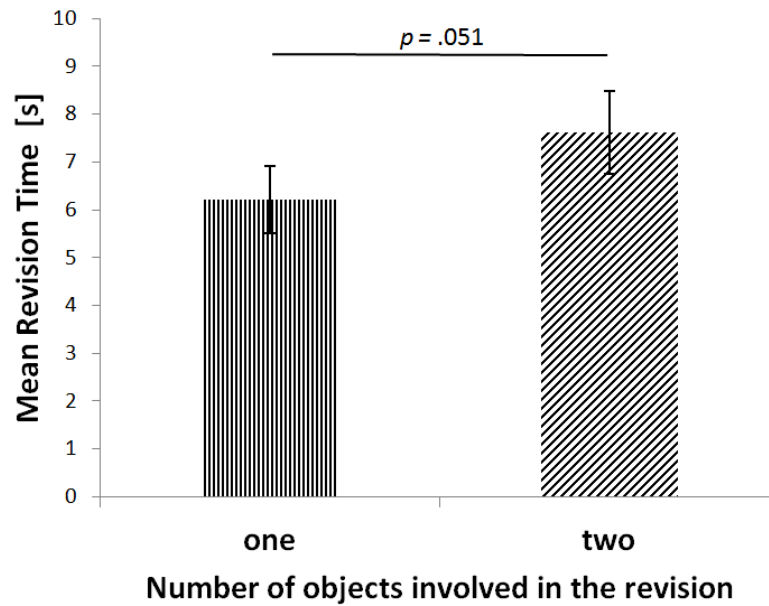


Figure 2. Mean revision times for revisions involving one and two objects are depicted. Error bars indicate standard errors.

General discussion

Reasoning about spatial relations encompasses multiple reasoning abilities. For instance, reasoners are able to assume how spatial arrangements look like when provided with verbal descriptions about relations of objects. Further, they are able to infer information that is not explicitly provided by the descriptions (Knauff et al., 1995; Knauff et al., 1998; Ragni et al., 2005). The reasoning processes underlying these abilities can be described as distinct phases that involve the construction, inspection, and variation of spatial mental models (Knauff et al., 1995; Knauff et al., 1998). Quite often new information run counter previously provided information. Inferences allow the detection of inconsistencies with conflicting information (Johnson-Laird et al., 2004a; Johnson-Laird et al., 2004b). In case, contradicting information can be considered as reliable or incontrovertible, it needs to be taken into account. Accordingly, reasoners are required to retract initial information and revise current beliefs in order to re-establish consistency within belief sets (Gärdenfors, 1992; Elio & Pellitier, 1997; Wolf & Knauff, 2008).

The ability of belief revision is an important one but little is known about its process. In the spatial context, belief revision is assumed to be accomplished by variation

of initially constructed spatial mental models. Variation itself is assumed to incorporate fact's information while conserving as much of the initial information as possible (Bucher et al., 2011; Krumnack et al., 2011a). Usually, there are several alternatives to vary initially constructed models that allow re-establishing consistency within belief sets; and the alternatives are frequently logically equivalent. Thus, logic does not help reasoners with their decision which alternative to prefer. Nevertheless, human reasoners prefer certain alternatives above others (Knauff et al., 1995; Ragni et al., 2005; Rauh et al., 2005; Jahn et al., 2007; Krumnack et al., 2010; Krumnack et al., 2011b). Studies on revision of spatial beliefs that examined determinants of preferences for variations of simple one-dimensional horizontal arrangements of three objects, showed that semantic cues of contrafactual information - verbally provided as binary relational statements - guide variations and lead preferably to variations based on the relocation of to be located objects (LOs) relative to reference objects (ROs) (Bucher et al., 2011; Krumnack et al., 2011a).

With the current work, we focused on the influence of the number of objects involved in model variation processes. From an economic point of view, changes to initially constructed models in the course of revision should be kept as minimal as possible. The assumption was that – given factors adherent to arrangements at hand influence revision - the number of objects attached to objects influence variation of initially constructed models. Variations involving the relocation of only one object should be preferably performed compared to variations involving the relocation of two objects. In two experiments, we examined whether reasoners follow this economic principle. However, in accordance with previous studies that show that reasoners focus on cues provided by inconsistent spatial information, we found preferences for variations that were based on the relocations of LOs relative to ROs in both experiments, when participants generated their revised arrangements freely (experiment 1) as well as when they choose from two alternative revised arrangements (experiment 2). Experiment 1 specifically corroborates fundamental assumptions about the revision process. Without exception, the participants' drawings indicated that revision was accomplished by variation of initially constructed models. As much of the initial information as possible was preserved.

With experiment 2, we looked deeper into the processing demand of variations as it emerges from relocating one compared to two objects. We assumed that higher complexity due to an increased number of objects increases processing difficulty, entailing increased processing demand. Variation that involved two, compared to one object, demanded higher cognitive resources. This was reflected by longer decision times. Results suggest that cognitively more economic principles are not necessarily guiding reasoning processes. LOs were preferably subject to relocation, regardless of whether their relocation implicated to relocate one (LO only) or two (LO and attached object) objects.

To summarize, our experiments show that variation is based on cues provided by contra factual spatial information. Although complexity did not affect the basic principle, it prolonged the revision process.

Given the importance of relational reasoning and the revision of beliefs for every-day life and the fact that every-day life's problems are rather complex, an important question remains: what exactly causes the additional demand on cognitive resources due to complexity during relational reasoning and in particular during the revision of spatial beliefs? Generally, the number of items, chunks, or units of information has been suggested to increase complexity (Miller, 1956). Relational load however is deemed not to be ascribable to item load per se (Halford et al., 1998; Phillips & Niki, 2002). It remains to specify what exactly increases complexity: the number of objects, relations, or dimensions; and how do these factors interact and impact or finally even guide relational reasoning processes?

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Part 3

Chapter 5

Construction and Revision of Spatial Mental Models under High Task Demand⁶

⁶ This work was published in a slightly different form in: Nejasmic, J., Bucher, L., Thorn, P.D., & Knauff, M. (2014). Construction and Revision of Spatial Mental Models under High Task Demand. In P. Bello, M. Guarini, M. McShane & B. Scassellati (Eds.), *Proceedings of the 36th Annual Conference of the Cognitive Science Society* (pp. 1066-1071). Austin, TX: Cognitive Science Society.

Abstract

Individuals often revise their beliefs when confronted with contradicting evidence. Belief revision in the spatial domain can be regarded as variation of initially constructed spatial mental models. Construction and revision usually follow distinct cognitive principles. The present study examines whether principles of revisions which follow constructions under high task demands differ from principles applied after less demanding constructions. We manipulated the task demands for model constructions by means of the continuity with which a spatial model was constructed. We administered tasks with continuous, semi-continuous, and discontinuous conditions as between-subject factor (experiment 1) and as within-subject factor (experiment 2). Construction and revision followed distinct cognitive principles in the changeless conditions of experiment 1. With increased task demands due to switches between different continuity conditions (experiment 2), reasoners adapted the principles they used for model revisions to the principles which they had used during antecedent constructions.

Introduction

Construction of spatial mental models

To cope with every-day life, humans in almost all situations have to make decisions on the basis of actual given or mentally stored information. Sometimes we are confronted with situations requiring different reasoning abilities. Imagine the following situation: You are talking to a friend who visited Paris and now tells you about his vacations. He says:

- (1) “The book store is to the left of the Eiffel Tower”
- (2) “And the café is to the left of the Champ de Mars”

Given these information it is not possible to determine how the buildings are related to each other. In particular, the two statements do not yet allow you to continuously arrange the named objects. It is assumed that humans process spatial information of this kind by constructing an integrated mental representation, called “mental model”. Mental

models represent what is true, given by the premises and in a more restricted sense how reality could be (Craik, 1943; Johnson-Laird & Byrne, 1991; Goodwin & Johnson-Laird, 2005).

The common notion is that human reasoning relies on the construction and inspection of mental models. We are inclined to integrate related pieces of information into one model and thus you would, most likely, start to think about the arrangement of the buildings (Johnson-Laird, 1983; Knauff, Rauh, & Schlieder, 1995; Knauff, Rauh, Schlieder, & Strube, 1998; Johnson-Laird et al., 2004; Goodwin & Johnson-Laird, 2005; Krumnack, Bucher, Nejasmic, Nebel, & Knauff, 2011; Nejasmic, Krumnack, Bucher, & Knauff, 2011). The construction of a mental model is influenced by a number of factors, among them the number of arguments; unambiguousness of the arguments, or the premise order (Ehrlich & Johnson-Laird, 1982; Evans, Newstead, & Byrne, 1993; Knauff et al., 1998; Nejasmic et al., 2011). The premise order determines how information is integrated into a spatial mental model. For instance, premises can be presented in a continuous (Ar_1B , Br_2C , Cr_3D), a semi-continuous (Br_2C , Cr_3D , Ar_1B), or a discontinuous order (Cr_3D , Ar_1B , Br_2C), with A, B, C, and D representing objects and r_n the relation (e.g. right of) between them.

These different premise orders result into different sequentially information integration and thus different cognitive demand. It is easier (faster and less error-prone) to construct models and draw inferences based on these models, when premises are given in a continuous and semi-continuous as opposed to discontinuous orders, known as the “continuity effect” (Ehrlich & Johnson-Laird, 1982; Knauff et al., 1998; Nejasmic et al., 2011). The continuity effect is usually explained as follows: humans process discontinuous information by constructing one temporary mental model which must be modified in order to match the last piece of information provided by the final premise of the discontinuous order. The construction of the temporary model basically equals the construction of a model based on continuous or semi-continuous information. However, the modification of the temporary model is an additional step which a) requires time and b) provides a source of errors. With a view to our introductory example this means that you

construct a temporary model (M1) from the first two statements, with a preferred working direction from left to right (Nejasmic et al., 2011):

(M1) Book store – Eiffel Tower – Café – Champ de Mars

The relation between the “Eiffel Tower” and the “Café” remains unconfirmed and is represented in the model only temporary. This temporary relation makes the difference between a temporary mental model and a “regular” mental model. Resuming the introductory example, imagine your friend provides you with a third piece of information:

(4) “The Champ de Mars is to the left of the book store.”

In the light of the additional information you are able to arrange the buildings in the correct order

(M2) Café – Champ de Mars – Book store – Eiffel Tower

The transition from the temporal – unconfirmed – model (M1) to the confirmed final model (M2) involves the relocation of objects. In our example, the objects “Café” and “Champ de Mars” are relocated within the temporary model to the model’s leftmost positions to come up with the final, confirmed arrangement (M2) (Nejasmic et al., 2011).

Once a model is constructed, the verbatim information of the premises gets lost to a great extent. What is stored in memory is the model as the “end product” (Ehrlich & Johnson-Laird, 1982). The retrieval of a model from the depth of your memory is supported by recordings of the vital steps that you had to accomplish while you constructed the model (Payne, 1993; Baguley & Payne, 1999, 2000; Payne & Baguley, 2006). It means the sequence by which the objects were integrated into the model and – most important for our study – the relocation of objects within the temporary mental model during the construction of the final model is traced.

Revision of spatial mental models

Let's extend our example by the component of belief revision. Revision is required when new evidence (partly) conflicts with information a reasoner received beforehand and thus runs counter his beliefs. To take contradicting information into account with the aim to re-establish consistency within a certain belief set, it is a vital need to perform a belief revision (Elio & Pelletier, 1994, 1997; Wolf, Rieger, & Knauff, 2012). Imagine that after a few minutes your friend's wife joined the conversation and told you:

(4) "Excuse me, I have lived in Paris for a long time and the Café is to the right of the Eiffel Tower."

The new piece of information seems reliable. To achieve consistency between the new fact and your previously held beliefs, you must modify your initially constructed mental model. Note, that there is more than one alternative for the revision of the arrangement

(R1) Champ de Mars – Book store – Eiffel Tower – Café

(R2) Eiffel Tower – Café – Champ de Mars – Book store

Despite the fact that both alternatives for re-establishing consistency are logically equivalent, there is evidence that reasoners have clear preferences for one alternative over the other (Bucher, Krumnack, Nejasmic, & Knauff, 2011; Krumnack, Bucher, Nejasmic, & Knauff, 2011; Bucher & Nejasmic, 2012; Bucher, Nejasmic, Bertleff, & Knauff, 2013; Knauff, Bucher, Krumnack, & Nejasmic, 2013; Nejasmic, Bucher, & Knauff, 2013).

For spatial belief revision three main assumptions were worked out: (1) The revision is deemed as a distinct phase, following a construction and subsequent inspection (implicating inconsistency detection as a prerequisite for a belief revision) of a spatial mental model. (2) The revision process has been suggested to rely on a variation of an initially constructed spatial model. (3) Spatial belief revision is sensitive to a functional

asymmetry between two arguments (located object – LO and reference object – RO) of a binary spatial relation and the LO, as the more “flexible” object of a verbatim spatial description is relocated within the initially constructed model. More precisely, applied to a spatial arrangement A – B – C and a contradicting fact “C is to the left of A” the object C is the located object and A is the reference object. Spatial belief revision is based on the relocation of the inconsistent fact’s LO, resulting in a preferred arrangement C – A – B (Bucher et al., 2011; Krumnack et al., 2011; Bucher & Nejasmic, 2012; Bucher et al., 2013; Knauff et al., 2013). Recent studies show that the LO-principle can be deemed as a strong cognitive principle for spatial belief revision processes that is modulate-able during reasoning about objects with specific properties (Nejasmic et al., 2013).

Construction and revision occur as independent processes, guided by distinct principles (e.g. Bucher et al., 2011). This seems the case at least under conditions that do not require much cognitive “effort” such as it is the case with tasks that allow “easy” model construction in a continuous way. We wondered whether reasoners still apply distinct principles for distinct reasoning phases in cases where more cognitive effort is needed for constructing one unified mental representation. For construction processes cognitive demand is increased with discontinuously presented information, compared to more continuously presented information (Ehrlich & Johnson-Laird, 1982; Knauff et al., 1998; Nejasmic et al., 2011).

We conducted two experiments, in which we manipulated the presentation order of premises. In experiment 1 reasoners were confronted with the premise orders as a between subject factor. Three groups received construction and revision problems of one kind: continuous, semi-continuous, or discontinuous. The question was whether “difficult” discontinuous constructions compared to “easy” continuous and semi-continuous constructions alter revisions. In the second experiment we went a step further and increased demand on cognitive resources during the construction phase even more. Reasoners were confronted with the problems of all three continuity conditions, randomly. That procedure created the necessity for reasoners to switch between tasks with different premise orders.

Our hypothesis is: with “difficult” constructions, spatial belief revision is accomplished by a repetition of processes already performed during the preceding construction phase. In these cases, we should find a repetition of object relocation to the leftmost side as it is performed during the integration of discontinuously presented information. With “easy” constructions, spatial belief revision remains based on the LO-principle.

Experiment 1

Method

Participants. Sixty-three students from the University of Giessen (23 male; age: $M = 23.3$; $SD = 2.7$) were tested individually. They gave written informed consent and were paid at a rate of 8€/hour for their participation. Data from four participants were excluded from the analysis due to errors on more than 90% of the problems. The experiment took approximately 30–45 min.

Materials, design, and procedure. Each participant solved 48 revision problems. Six practice trials (not analyzed) preceded the experimental trials. Participants received all instructions on the computer screen. The structure of the problems was as follows: participants received in a “construction phase” sequentially (in a self-paced manner) three statements (1, 2, and 3) which described the spatial relation of four small, equal-sized and disyllabic objects (tools, fruits, and vegetables), for example:

- Premise 1: “Apple left of mango”
Premise 2: “Mango left of kiwi”
Premise 3: “Kiwi left of pear”

Participants were randomly assigned to one of the premise-order condition: continuous ($n = 19$), semi-continuous ($n = 20$), and discontinuous ($n = 20$) and thus received problems in only one premise order throughout the experiment. They were instructed to imagine the arrangement described by the three premises (in this case apple–

mango–kiwi–pear) and subsequently to choose one out of two arrangements (correct arrangement / correct arrangement mirrored), presented on the screen, by pressing the corresponding button on the response pad.

In a subsequent “revision phase”, an additional statement was presented that was introduced as an incontrovertible “fact”. It was either consistent, in half of the problems (“Apple left of pear”) or inconsistent in the other half (“Pear left of apple”) with the information provided by the premises. Participants were told that the fourth statement is irrefutably true and that they have to take it into account. They had to decide whether or not the presented fact is consistent with the initial model, by pressing the respective button (“yes” or “no”). In cases where participants decided that the fact was inconsistent, they were asked to revise the arrangement (resulting in either pear–apple–mango–kiwi (“relocation of the LO to the left”) or alternative in mango–kiwi–pear–apple (“relocation of the RO to the right”) and subsequently to choose one out of the two revised arrangements presented on the screen by pressing the corresponding button. If participants decided that the fact is consistent with the initial premises and the arrangement the trial finished at this point and the next one was presented.

All statements were presented in black on a white background (beside the fact which was presented in red to highlight it). Premises were presented with the relation “left of” only. However, the facts used the relations “left of” and “right of”, indicating the direction in which the fact’s LO or RO could be relocated. Thus the experiment was designed in a way that in half of the revision problems a fact’s LO could be relocated to the leftmost side of the initial arrangement (with the alternative possibility to relocate a RO to the right) and in the other half of the problems the reverse was the case. Positions of the arrangements as well as positions of decision buttons (“yes” and “no”) were counterbalanced across the experiment.

All stimuli were generated and presented using Superlab 4.0 with an RB-530 response box (Cedrus Corporation, San Pedro, CA, 1999-2006). The experiment was run on a standard personal computer (Windows XP) with a standard 19” monitor. Premise reading times (respective time from text onset to button press calling up the next premise),

number of correct decisions in the “construction” and “inconsistency detection phase”, type of revisions in the “revision phase”, and corresponding revision times were recorded.

Results and discussion

Construction. To ensure, that the manipulation of different premise orders worked, an ANOVA with the within factor premise number (first, second, third premise) × and the between factor premise order (continuous, semi-continuous, discontinuous) was conducted for reading times. Level of significance was 5%.

ANOVA revealed a significant main effect of premise number, $F(2, 112) = 6.01$; $p = .003$; $\eta^2 = .10$, and a significant interaction between the factors, $F(4, 112) = 10.61$; $p < .001$; $\eta^2 = .28$. Subsequent t -tests revealed that reading times for first premises were significantly longer in the discontinuous, than of the continuous condition, $t(37) = -2.27$; $p = .030$, $d = 0.74$. Participants needed more time for reading second premises of semi-continuous, $t(37) = -2.21$; $p = .033$, $d = 0.73$, and of discontinuous orders, $t(37) = -4.67$; $p < .001$, $d = 1.54$, than of the continuous condition. For third premises reading times were longer in the discontinuous condition than of the continuous, $t(37) = -6.31$; $p < .001$, $d = 2.03$, as well as semi-continuous condition, $t(38) = -4.46$; $p < .001$, $d = 1.45$. Equally, participants needed more time reading third premises of semi-continuous, than of continuous orders, $t(37) = -3.99$; $p < .001$, $d = 1.31$. All other analyses were non-significant (all $ps > .06$) (for an overview see table 1).

Table 1
Mean reading times for the three premises depending on the premise orders continuous, semi-continuous, and discontinuous for experiment 1

| Premise order | Premise 1 | Premise 2 | Premise 3 |
|----------------|---------------|---------------|---------------|
| | <i>M (SD)</i> | <i>M (SD)</i> | <i>M (SD)</i> |
| Continuous | 3.39 (1.50) | 2.01 (1.38) | 1.89 (0.95) |
| Semicontinuous | 3.62 (1.47) | 3.20 (1.93) | 3.18 (1.06) |
| Discontinuous | 4.56 (1.71) | 4.29 (1.65) | 6.39 (3.04) |

Participants performed the construction part well, choosing correct arrangements in 97% ($SD = 3.8$) of the trials. Inconsistencies between the initial description and the

contradictory fact were correctly detected in 91% ($SD = 9.0$) of the cases. Erroneous trials were excluded from further analyses.

Revision. ANOVAs with the factors premise order (continuous, semi-continuous, discontinuous) \times LO relocation direction (left vs. right) were conducted for revision choices and respective revision times. Level of significance was 5%.

ANOVA revealed no significant differences, neither for relocation directions of a LO, nor for corresponding revision times depending on different premise orders (all $ps > .45$). However, results from an additional analysis revealed that the LO was relocated preferably ($M = 71\%$; $SD = 19.5$) compared to the RO ($M = 29\%$; $SD = 19.5$), Wilcoxon test, $z = -5.61$, $p < .001$, (see figure 1).

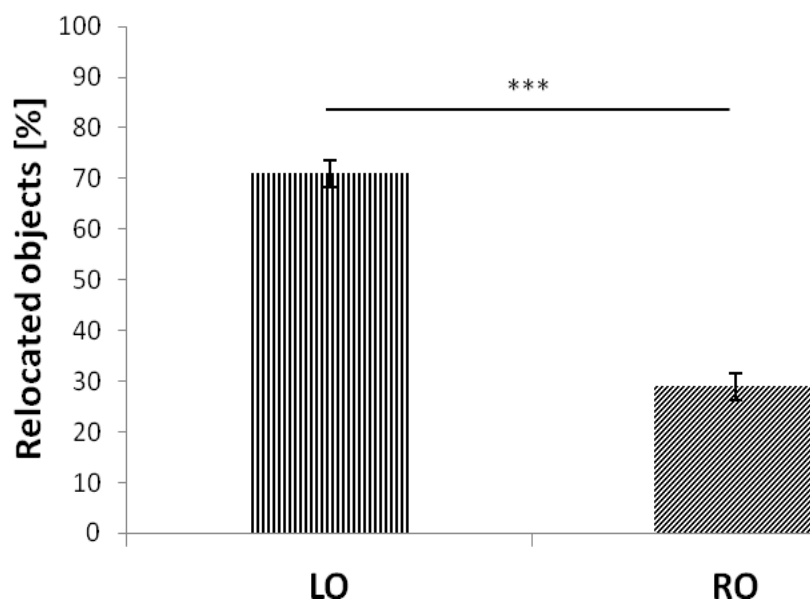


Figure 1. Relative frequency (in%) of model choices based on the relocation of a fact's LO vs. RO in experiment 1. Error bars show standard errors.

The reading times show a continuity effect. Participants needed not only more time to process discontinuous problems in general, but they were also slower in processing first premises compared to continuous problems. It seems that a more difficult construction in combination with a subsequent revision takes its toll on cognitive resources, reflected by higher reading times. However, reasoners were able to switch to their preferred revision strategy, the LO relocation, which they applied even in the most complex problems. We

conducted a second experiment in which we manipulated the difficulty of the task additionally by a random presentation of premise orders resulting in the necessity to switch between the premise orders.

Experiment 2

Method

Participants. Another sample of 32 students from the University of Giessen (3 male; age: $M = 23.1$; $SD = 2.4$) were tested individually. They gave written informed consent and were paid at a rate of 8€/hour for their participation. Data from seven participants were excluded from the analysis due to errors on more than 90% ($n = 2$) of the problems or extremely long reading times ($n = 5$). The experiment took approximately 30–45 min.

Materials, procedure, and design. Instructions on the computer screen and the procedure were the same as in experiment 1 with the exception that premises were presented randomly in the three premise orders (continuous, semi-continuous, or discontinuous) to each participant. Thus all participants were confronted with all three types of premise orders throughout the experiment.

Results and discussion

Construction. Again, an ANOVA with the factors premise number (first, second, third) \times premise order (continuous, semi-continuous, discontinuous) was conducted for reading times. Level of significance was 5%.

ANOVA revealed significant main effects of premise number, $F(2, 48) = 12.06$; $p < .001$; $\eta^2 = .33$, and premise order, $F(2, 48) = 34.35$; $p < .001$; $\eta^2 = .59$, as well as a significant interaction premise number \times premise order, $F(4, 96) = 7.47$; $p = .002$; $\eta^2 = .24$. Based on results known from previous studies describing the continuity effect, we are mainly interested in the significant interaction. Premise reading times depending on different premise orders were compared separately using t -tests. Participants needed more time for reading second premises of discontinuous than of continuous orders, $t(24) = -4.69$; $p < .001$, $d_z = 0.90$, as well as of semi-continuous orders, $t(24) = -4.63$; $p < .001$, $d_z = 0.98$.

For third premises, reading times were longer in the discontinuous condition than in the continuous, $t(24) = -6.67$; $p < .001$, $d_z = 1.23$, as well as semi-continuous condition, $t(24) = -4.58$; $p < .001$, $d_z = 0.82$. Equally, participants needed more time for processing third premises of semi-continuous than of continuous orders, $t(24) = -5.09$; $p < .001$, $d_z = 1.00$. All other analyses were non-significant (all $ps > .35$) (see Table 2).

Table 2
Mean reading times for the three premises depending on the premise orders continuous, semi-continuous, and discontinuous for experiment 2

| Premise order | Premise 1 | Premise 2 | Premise 3 |
|----------------|---------------|---------------|---------------|
| | <i>M (SD)</i> | <i>M (SD)</i> | <i>M (SD)</i> |
| Continuous | 5.09(1.63) | 4.10(2.17) | 4.81(1.83) |
| Semicontinuous | 5.14(1.89) | 4.08(2.10) | 6.25(2.05) |
| Discontinuous | 5.77(3.81) | 5.70(2.63) | 9.19(4.07) |

Similar to experiment 1, participants performed the construction part well, by choosing correct arrangements in 92% ($SD = 11.5$) of the trials. Inconsistencies between the initial information and the contradictory fact were correctly detected in 84% ($SD = 20.22$) of the cases. Erroneous trials were excluded from further analysis.

Revision. ANOVAs with the factors premise order (continuous, semi-continuous, discontinuous) \times LO relocation direction (left, right) were conducted for revision choices and respective revision times. Level of significance was 5%.

ANOVA for revision choices revealed a significant main effect of LO relocation direction, $F(1, 21) = 7.65$; $p = .012$; $\eta^2 = .27$. A subsequent t -test revealed that participants relocated more often a LO to the leftmost side ($M = 79\%$; $SD = 27.1$) than to the rightmost side ($M = 58\%$; $SD = 32.3$), $t(24) = 2.52$; $p = .019$, $d_z = 0.51$, (see figure 2). All other analyses were non-significant (all $ps > .15$).

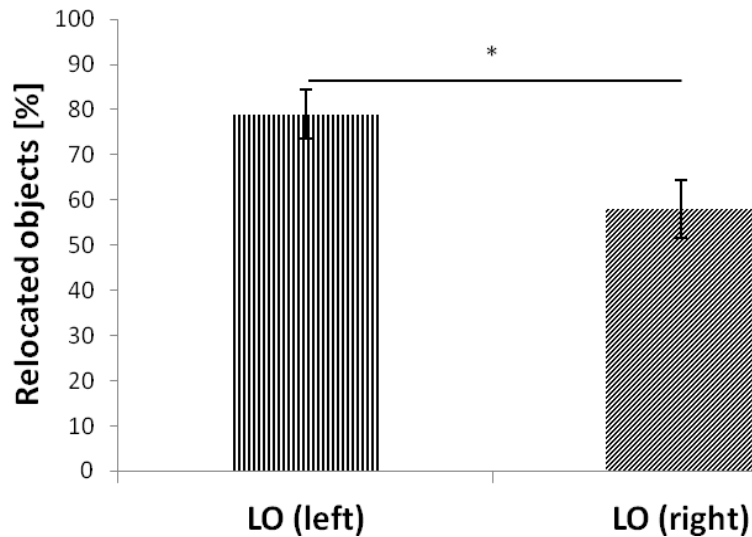


Figure 2. Relative frequency (in%) of model choices based on the relocation of a fact's LO to the leftmost side vs. the rightmost side of a spatial mental model. Error bars show standard errors.

Again, results for the construction phase suggest that the manipulation worked and more cognitive effort was used in semi-continuous or discontinuous conditions. By switching between different premise orders we intended to force less available capacities for the revision phase. Results show that participants preferred a LO-principle that implies a relocation direction to the left, compared to a LO-relocation to the right. As mentioned before, participants had the possibility to choose between two revised arrangements, following either the LO-principle, or the RO-principle. In previous studies participants almost ignore the logical equivalent RO-principle but in the present study the relocation direction modulates the revision strategy. Participants chose more often the RO-relocation, in cases where the relocation direction was to the left, compared to a LO-relocation to the right.

General discussion

The revision of spatial beliefs has been suggested to be based on a variation of an initially constructed spatial model. Reasoning during the construction and the revision phase can be described in two distinct phases with distinct underlying cognitive processes

involved in respective reasoning processes. However, phases may also share characteristic processes and preceding processes may also affect subsequent processes.

The present work investigates whether increased difficulty of the construction process affects revision and whether cognitive principles which are distinct for construction and revision under conditions which are cognitively not demanding, change under high task demands. In particular, we were interested whether relocations already performed during the construction phase were repeated for revisions when demands are high. In two experiments, participants solved problems with varying premise orders (continuous, semi-continuous, and discontinuous order). In experiment 1, reasoners were confronted with one kind (e.g. continuous), in experiment 2, with all kinds of presentation orders in a random manner, further increasing demands on cognitive resources during the construction phase. In both experiments, we replicated the continuity effect that occurs during the construction of a spatial model, i.e. reading times as measured between subjects (experiment 1) and across the problems within subjects (experiment 2) - expectedly - differed depending on premise orders. More time was needed for discontinuous problems compared to continuous and semi-continuous problems, reflecting higher cognitive demands on the integration of premise information in a discontinuous compared to a more continuous order.

While in experiment 1, reasoner's revision processes were guided by semantic cues yielded by inconsistent statements (LO-principle) a different pattern emerged in experiment 2. When discontinuous problems were randomly presented together with continuous and semi-continuous problems, revisions were overall preferably based on relocations of objects contingent on the relocation direction performed during the construction phase. This indicates an influence of reasoning processes performed during the construction phase on subsequent revision.

Interestingly, the effect did not occur in experiment 1, when reasoners solved only one kind of problems and were not required to switch flexibly between different premise orders. The different pattern emerging during the revision phase in experiment 1 compared

to 2 can be interpreted in the way that it is easier and more parsimonious to manipulate mental models than storing/using initial descriptions and vital steps of preceding phases.

Participants in experiment 1 adapted very well to the particular task demand when confronted with only one type of premise order, and they did so, even when confronted with the most difficult – the discontinuous – premise order. Cognitive resources in experiment 1 were presumably very efficiently allocated to the subsequent revision phases. However, the necessity of switching between different premise orders in experiment 2, increased the difficulty of construction processes, engaging more cognitive resources. As a result, the subsequent revision processes were modulated and influenced by the construction processes performed previously, using the episodic trace recorded during construction to accomplish the revision. Constructing a mental model on the basis of discontinuously presented information requires mental operations, similar to a mental relocation performed during revision. In this sense the modification of a temporary mental model can be described as a revision-like process that is repeated during spatial belief revision in cases when less cognitive capacities resources are available.

We conclude: increased difficulty of the construction of spatial models leads to a higher demand of cognitive resources which in turn modulates operations performed during the subsequent reasoning phase of revision.

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Part 4

Chapter 6

Grounded Spatial Belief Revision⁷

⁷ This work is in a slightly different form in press: Nejasmic, J., Bucher, L., & Knauff, M. (in press). Grounded Spatial Belief Revision. *Acta Psychologica*.

Abstract

Beliefs frequently undergo revisions, especially when new pieces of information are true but inconsistent with current beliefs. In previous studies, we showed that linguistic asymmetries provided by relational statements, play a crucial role in spatial belief revision. Located objects (LO) are preferably revised compared to reference objects (RO), known as the LO-principle. Here we establish a connection between spatial belief revision and grounded cognition. In three experiments, we explored whether imagined physical object properties influence which object is relocated and which remains at its initial position. Participants mentally revised beliefs about the arrangements of objects which could be envisaged as light and heavy (Experiment 1), small and large (Experiment 2), or movable and immovable (Experiment 3). The results show that intrinsic object properties are differently taken into account during spatial belief revision. Object weight did not alter the LO-principle (Experiment 1), whereas object size was found to influence which object was preferably relocated (Experiment 2). Object movability did not affect relocation preferences but had an effect on relocation durations (Experiment 3). The findings support the simulation hypothesis within the grounded cognition approach and create new connections between the spatial mental model theory of reasoning and the idea of grounded cognition.

Introduction

Imagine you have a date with a friend in a foreign city. He described to you how to get to the meeting point: "When you get off the train, you will see the kiosk to the left of you, and an ice cart to the right of you. To the left of the kiosk, I will wait for you." This description is compatible with the following mental model:

Kiosk – I – ice cart

Almost arriving you receive a phone call from your friend who tells you: "I made a mistake. The kiosk is to the right of the ice cart". On which side is your friend waiting for you? In fact there are two possibilities:

I – ice cart – kiosk

Ice cart – kiosk – I

In everyday life, we are often confronted with such problems. People describe how to find certain objects and then realize that the description is wrong ("I left your key on the kitchen table, but it is actually on the table in the living room"); someone describes how to find a certain place in a foreign city and on your way, you realize that his description was wrong; your partner describes where he parked your car, but it is parked somewhere different, and so on. All this has to do with the field of "belief revision". Researchers in this field explore how people change their mind in the light of new contradicting information. The experimental studies mostly used conditional reasoning problems in which an inconsistency arises between a fact, contradicting a valid conclusion, and the conditional and categorical premises. Within this research, psychologists were able to show that belief revision is affected by many factors, including asymmetries between particular facts and general laws (Revlis, Lipkin, & Hayes, 1971), conditional and categorical premises (Elio & Pelletier, 1997; Dieussaert, Schaeken, De Neys, & d'Ydewalle, 2000; Girotto, Johnson-Laird, Legrenzi, & Sonino, 2000; Revlin, Cate, & Rouss, 2001), major and minor premises (Politzer & Carles, 2001), and reliable and unreliable information sources (Wolf, Rieger, & Knauff, 2012).

The present work is part of our endeavor to (1) extend the cognitive research on human belief revision to the area of spatial reasoning and (2) to combine this research with the idea that cognitive processes are not only abstract symbolic manipulations but grounded in perceptual, motoric, or emotional experience (for an overview, see de Vega, Graesser, & Glenberg, 2008). Imagine, for instance, you are helping a friend to move into a new apartment. You have to carry many things (sofas, tables, books, porcelain, washing machine, hopefully no piano, etc.) from his old apartment to the furniture truck and then

later from the furniture truck into the new apartment. It is very likely that you try to avoid carrying bulky objects and prefer to move objects which are easy to carry. The question arises whether the physical properties of the objects that we reason about have an effect on how we think about them and how we manipulate them in our mental representation. All experiments on spatial belief revision so far used objects such as mangos, oranges, apples etc. that can be considered "neutral" regarding their specific physical properties (e.g., Knauff, Bucher, Krumnack, & Nejasmic, 2013). These objects are very similar regarding physical properties, weight, size, and so on and it has not been investigated so far whether properties of objects affect the process of reasoning. However, recent theories on "grounded" and "embodied" cognition suggest that bodily experiences with and physical properties of objects indeed matter when we reason about them, even if the properties are not relevant for the cognitive task at hand (Barsalou, 2007; Zwaan & Pecher, 2012; Glenberg, Witt, & Metcalfe, 2013). That is, although you just imagine you are moving your friends' furniture you might prefer to reason about carrying a vase over towing a piano, although that all happens in your mind without any real physical effort. The aim of this paper is to study such effects of *grounded cognition* in the area of spatial belief revision, when people have to mentally – but not physically – relocate objects in their imagination to account for newly available information during reasoning.

The structure of this article is as follows. First, we report some empirical findings on the link between grounded cognition, spatial reasoning, and belief revision. Second, we describe how our research is related to previous work on spatial mental models and then develop our hypotheses on how physical object properties should impact mental spatial belief revision. Third, we test these hypotheses with three experiments. Finally, we discuss our findings and draw some general conclusions on the connection of mental models, grounded cognition, and spatial belief revision.

The link between grounded cognition, spatial reasoning, and belief revision

The theory presented in this paper postulates that when individuals are confronted with a spatial belief revision problem, they first construct a mental model of the described

state of affairs. If they are confronted with new information which is inconsistent with this initial model they vary the model in order to obtain consistency (Johnson-Laird, Girotto, & Legrenzi, 2004; Ragni & Knauff, 2013; more details are described below). The experiments concern the question if and to what extent the properties of objects such as size, movability, weight, and the potential bodily experience with these properties in the physical world affect the model variation process. For example, when people carry small or bulky objects this engages their muscles in the arms and legs differently. The hypothesis that we test in this paper is that during mental reasoning people simulate this bodily strain in their imagination and therefore also prefer to move handy sized objects over bulky ones in their mental representation. The theoretical background and the empirical evidence for this assumption are as follows.

Grounded cognition and object properties

Classical theories of human cognition rely on the idea that human thinking is based on an abstract language of thought (Fodor, 1975; Pylyshyn, 1984; Anderson, 1993). Arbitrary symbols stand for what they represent and humans are equipped with mental procedures to combine and manipulate these abstract symbols. The results of such syntactic mental operations are again abstract symbol structures. Meaning arises from the combination of symbols that are arbitrarily related to what they signify (Glenberg & Robertson, 2000). The body and the information from the brain's modal systems for perception and action play, if any, just a marginal role because the symbols represent meaning in an abstract way that does not capture modality-specific information about the physical properties of objects, actions, or events. This classical approach is supported by numerous experimental findings and was very important for the development of cognitive psychology (e.g. Anderson, 1983, 1993; Rips, 1994; Pylyshyn, 2006; Adler & Rips, 2008). Today this classical approach is criticized by many psychologists. Some argue that the approach must be complemented by theories paying more attention to the representation of bodily experiences (Barsalou, 2007). Others are even more radical and completely deny the existence of abstract symbols in the human mind (e.g., Glenberg et al., 2013). The

common idea of all these approaches is that people's understanding of language and memory representations is grounded in their physical interactions with the world (Beveridge & Pickering, 2013).

In fact, many authors reported that the processing of information in the mind is largely affected by the physical characteristics of the human body. For example, Glenberg and Kaschak (2002) asked participants to make judgments on sentences that describe actions toward the body (e.g., "Mark dealt the cards to you") or away from the body (e.g., "You dealt the cards to Mark"). The authors found that participants responded faster when the response requires an arm movement in the same direction as the action described by the sentence, which is called the Action-Sentence Compatibility Effect. Stanfield and Zwaan (2001) found that participants can respond faster to a picture of a *vertical* nail following the sentence "Mary pounded the nail into the floor" than after the sentence "Mary pounded the nail into the wall". The reverse response times were found for a picture of a *horizontal* nail. Proffitt (2006) studied visual perception and showed that people overestimate distances when wearing a heavy backpack or when of low physical fitness. Based on these findings, Proffitt argued that the perceived distance is affected by the bodily effort needed to traverse the distance.

The reported findings are only a few under many other results suggesting that simulated bodily states can affect mental states (Lakoff & Johnson, 1980; Barsalou, Simmons, Barbey, & Wilson, 2003; Smith, 2005; Barsalou, 2008). The theory of grounded cognition is also supported by functional brain imaging studies showing that the neural systems for meaning and action are reciprocally connected with each other (Isenberg et al., 1999; Martin & Chao, 2001; Gernsbacher & Kaschak, 2003; Kan, Barsalou, Solomon, Minor, & Thompson-Schill, 2003; Zwaan, Taylor, & De Boer, 2010; for an overview see: Pulvermüller, 1999).

Of particular importance for the present topic are cognitive studies on the effect of cognizing object properties such as size, weight, or movability. The question here is whether or not things that are hard to physically move are also hard to imagine moving. Flusberg and Boroditsky (2011) investigated this question by asking participants to

manipulate wooden objects similar to the figures in the classic mental rotation experiment by Shepard and Metzler (1971). In the experiments, the wooden objects were mounted on rotation platforms with either empty devices or devices filled with sand. Thus, one pair of objects was easy to physically rotate while another pair was difficult to rotate, because of the sand. Flusberg and Boroditsky (2011) reported that participants were slower to mentally rotate objects that were harder to physically rotate. Object properties obviously had an effect on motor imagery. Similar results are reported in a study by Amorim, Isableu, and Jarraya (2006), who could demonstrate a cognitive advantage of imagined spatial transformations of the human body over that of more unfamiliar objects. These results, along with related findings have been used to argue that there is a close relationship between perceptual and motoric experiences and mental imagery (Kosslyn, Thompson, & Ganis, 2006; Barsalou, 2008).

A further characteristic of grounded cognition is to emphasize the importance of perspective taking in spatial thinking and language. Perspective taking means that it matters whether people mentally represent a scene from their own or a different spatial perspective (Rizzolatti & Arbib, 1998; Kosslyn, Ganis, & Thompson, 2001; Pulvermüller, 2005). Further, and probably more important, for embodiment theories it also matters whether persons simulate an action as if they were performing the action, or as if another person performs the action (Beveridge & Pickering, 2013). In the present paper, we account for perspective-taking by explicitly asking the participants to image to be part of the scene. Thus, our problem always consisted of two objects and the participant as a third “object”. An example for our problems is: "The piano is to the left of you.", "You are to the left of the sofa." How are the named objects arranged? In the next step a contradictory fact was presented, as we describe below.

Several studies suggest that our phrasing of the problems lead a participant to mentally simulate executing an action himself or herself. For instance, some authors could show that humans adopt a perspective automatically for sentences in which a self-referential pronoun is used and specifies the person as the agent of the action (Hauk, Johnsrude, & Pulvermüller, 2004; Pulvermüller, Hauk, Nikulin, & Ilmoniemi, 2005;

Willems, Hagoort, & Casasanto, 2010). Rizzolatti and Arbib (1998) showed that only if people imagine active physical interactions with objects this results in activity in areas of the motor cortex (see also: Kosslyn, Ganis, & Thompson, 2001; Pulvermüller, 2005). Other studies showed that a certain perspective and additional bodily information may facilitate human reasoning (MacWhinney, 2005; Flusberg & Boroditsky, 2011; Beveridge & Pickering, 2013; Galati & Avraamides, 2013).

Spatial reasoning with mental models

The grounded cognition theory has been applied to many areas of psychology including concept representation (Barsalou, 1999), memory (e.g. Glenberg, 1997), language understanding (Glenberg & Kaschak, 2002; Zwaan, 2004), and social psychology (Barsalou et al., 2003). However, it has not yet been connected to the area of human reasoning, in which psychologists explore how people infer new information from what is already given (Johnson-Laird, 1991, 2006, 2010; Knauff, 2013). The lack of such a connection is surprising as the dominant theory of reasoning, the theory of mental models, and the grounded cognition framework share many basic assumptions. The central assumption that both theories have in common is that human cognition relies on *mental simulations*. Grounded cognition postulates that people understand sentences by mentally simulating what is described in the sentences. And it is assumed that humans reason by mentally simulating the content of an inference problem and then inspecting this model to find new information not explicitly given. In fact, both theories (grounded cognition and mental models) are also historically intimately linked (Bower, 1972; Kintsch & van Dijk, 1978; Johnson-Laird, 1989; Glenberg & Robertson, 1999).

Today the vast majority of reasoning researchers considers the theory of mental models as the empirically best supported theory of human *spatial reasoning* (Johnson-Laird & Byrne, 1991; Knauff, Rauh, & Schlieder 1995; Vandierendonck & de Vooght, 1997; Knauff, Rauh, Schlieder, & Strube, 1998; Schaeken, Girotto, & Johnson-Laird, 1998; Ragni, Knauff, & Nebel, 2005; Rauh, Hagen, Kuss, Knauff, Schlieder, & Strube, 2005; Krumnack, Bucher, Nejasmic, & Knauff, 2010; Krumnack, Bucher, Nejasmic,

Nebel, & Knauff, 2011b; for an exception see: van der Henst, 2002). According to Johnson-Laird (Johnson-Laird, 1983, 2006, 2010; Johnson-Laird & Byrne, 1991) a mental model is a mental simulation of the information presented in the reasoning problem. That is, the diverse pieces of information from the premises are not kept as separate entities in the reasoners mind. Rather, they are merged into a model that simulates the information given in the problem description, when it is constructed consistently. According to the model theory, people translate a perceived or imagined situation into such a mental model and use this representation to solve associated inference problems (Johnson-Laird, 1983, 2001, 2006, 2010; Johnson-Laird & Byrne, 1991). A central assumption of the model theory is that a reasoning process consists of three separate phases, which Johnson-Laird calls the comprehension, description and validation phases (Johnson-Laird & Byrne, 1991). In our previous publications, we suggested to use the terms *model construction*, *model inspection*, and *model variation phase*, because these terms characterize better what actually happens in these phases (Knauff et al., 1998; Nejasmic, Krumnack, Bucher, & Knauff, 2011; Knauff, 2013). In the model construction phase, people use the semantics of spatial expressions to construct an internal model of the state of affairs that the premises describe. In the model inspection phase, a parsimonious description of the mental model is constructed, including a preliminary conclusion. In other words, the mental model is inspected to find out relations not explicitly given. In the model variation phase, people vary the model in order to find alternative models.

The present paper is primarily concerned with the model variation phase, in which people must vary an already constructed model to account for new inconsistent information. In our previous work, we have postulated three main principles for such spatial revision processes (Knauff et al., 2013):

1. Spatial belief revision is based on the construction and inspection of mental models. If given premises are true, a unified mental model represents what is believed to be true. By using the meaning of assertions and general knowledge a single model of possibilities that is compatible with these assertions is constructed. Explicitly given

spatial information are not represented one-to-one mentally, rather they are inherent in the mental model. In this way relations between objects can be identified by mental inspection processes (Johnson-Laird & Byrne, 1991; Polk & Newell, 1995; Goodwin & Johnson-Laird, 2005).

2. Spatial belief revision relies on the revision of mental models. Individuals revise a model if newly available information is inconsistent with the current model and the new information must be taken for granted. In this process, people first "decide" which of the information to retain and which one to discard. Afterwards a local transformation is accomplished in which tokens are moved within the model to new positions (Bucher, Krumnack, Nejasmic, & Knauff, 2011; Krumnack, Bucher, Nejasmic, & Knauff, 2011a; Bucher & Nejasmic, 2012).
3. The model revision process is sensitive to the functional asymmetry between the "reference object" (RO) and the "located object" (LO). Previous authors suggested an asymmetric role of the two arguments in a verbatim spatial description: The RO is interpreted as a landmark whose location is fixed and known, whereas the LO is located in relation to the RO and seems to be spatially more flexible. The common idea of all these accounts is that a spatial relation refers to the position of a particular object in focus relative to another object or area (Miller & Johnson-Laird, 1976; Talmy, 1983; Landau & Jackendoff, 1993; Tenbrink, Andonova, & Coventry, 2011). For instance, assuming that an initial model A – B – C is constructed and an inconsistent, but incontrovertible statement "A is to the right of C" is given. In this case is C the RO and A the LO. To regain consistency between the model and the inconsistent statement, the LO (A) of the inconsistent statement is relocated within the initially constructed mental model (resulting in a model B – C – A), also known as the LO-principle (Bucher et al., 2011; Krumnack et al., 2011a; Bucher & Nejasmic, 2012; Knauff et al., 2013; Bucher, Nejasmic, Bertleff,

& Knauff, 2013; Mikheeva, Bucher, Nejasmic, & Knauff, 2013; Nejasmic, Bucher, Thorn, & Knauff, 2014).

In the present research, we use the stability of the LO-principle and test whether the effect is modulated by a person's bodily experiences with the interaction and manipulation of objects in the real world. Can the embodied aspects of the objects in a model weaken the LO-principle? Does the physical weight, size, or movability of the objects in the mental model influence how the model is revised? Based on previous findings within the grounded cognition framework, we predict that object properties such as weight, size, and movability indeed should affect the revision process. In general, we assume that the effect of the LO-principle can be weakened when the LO represents an object with a "disadvantageous" physical property (heavy, large, or unmovable) compared to an LO with a comparably "advantageous" property (light, small, or movable). When reasoners make use of mental simulations during the revision process, we expect them to mentally simulate the action of relocating real objects in the physical world. Thus, our main assumption is that objects with "advantageous" properties should be relocated more often or faster compared to the "disadvantageous" objects in the mental model. We also expect that these effects should be differently pronounced for different object properties, such as size, weight, or movability.

We now present three experiments that tested these hypotheses. In the experiments, participants received information about the spatial relations between objects which were either light or heavy (Experiment 1), small or large (Experiment 2), or movable or immovable (Experiment 3). The participants' task was to revise an initially constructed mental model after receiving a new contradicting piece of information. Prior to the main experiments, we conducted a pilot study during which participants rated objects according to a number of physical properties. The most appropriate items were subsequently chosen as objects for the main experiments.

Pilot study

Our first task was to define the set of objects for our experiments. One option would be to use the actual physical measures. However, we decided that for a psychological study it is more important how the objects are mentally represented and how people judge the weight, size, and movability of diverse objects. Certainly, the physical and the “psychological” proportions should be highly correlated and there should also be a correlation between weight, size, and movability (in the present study the ratings correlated as follows: size-weight: $r = .86$, $p = .000$, $N = 60$; size-movability: $r = .51$, $p = .000$, $N = 64$). To avoid confounds between the properties within experimental objects, we used only these objects from the large sets of objects rated in the pilot study whose ratings correlated least. Objects chosen for the pilot study were split into two sets of objects, rated by two different samples of participants in order to avoid lengthy rating experiments for the participants. The first list consisted of 60 objects. The objects were rated by 44 participants according to weight and size on five-point scales with the poles “very light” to “very heavy” and “very small” to “very large”. The objects were presented in randomized orders to the participants. We selected the objects that obtained the lowest and highest mean values on the weight-scale and medium values on the size-scale (in order to control for the object size), for experiment 1. The second list consisted of another set of 64 objects (different objects than the first list), and was presented to a new sample of 46 participants. Participants rated the objects on five-point scales with the poles “very small” to “very large” and “very movable” to “very immovable”, respectively. With this procedure it was possible to select objects that differed in their size but were rated as similar regarding their movability (and vice versa). Objects that obtained the lowest and highest mean values on the size-scale and mean values on the movability-scale were used in experiment 2. Objects that were rated as lowest and highest regarding movability but comparable in size were used in experiment 3. It is important to note that some objects of our pilot study are inherently movable or immovable and were rated by participants accordingly. For instance, our participants rated a “printer” as relatively small but immovable (due to the

wiring), whereas they rated a “soccer ball” as small and highly movable. All objects used in the experiments and corresponding means are presented in table 1.

Table 1
Objects used in the experiment according to their property with respective means and correlations

| light | heavy | small | large | movable | immovable |
|--------------------|--------------------|------------------------|------------------------|------------------------|------------------------|
| fishing rod | jukebox | screen | power mast | wheelchair | pillar |
| beach towel | sofa | vase | bridge | bicycle | counter |
| sleeping bag | icebox | printer | railway station | carriage | gravestone |
| sheet | stone bench | post | high rise | scooter | oven |
| curtain | piano | lamp | spire | barrow | hydrant |
| <i>M(SD)</i> | <i>M(SD)</i> | <i>M(SD)</i> | <i>M(SD)</i> | <i>M(SD)</i> | <i>M(SD)</i> |
| size/weight | size/weight | size/movability | size/movability | size/movability | size/movability |
| 3.0(0.8)/1.9(0.8) | 4.1(0.7)/4.6(0.6) | 2.4(0.6)/2.8(1.0) | 4.6(0.5)/1.2(0.5) | 3.0(0.6)/4.1(0.8) | 3.0(0.7)/1.5(0.7) |
| $r=.37, p=.542$ | $r=.29, p=.639$ | $r=-.88, p=.051$ | $r=-.73, p=.165$ | $r=-.80, p=.106$ | $r=.45, p=.449$ |
| $r^2=.14$ | $r^2=.08$ | $r^2=.77$ | $r^2=.53$ | $r^2=.64$ | $r^2=.20$ |

Experiment 1: light vs. heavy objects

The first experiment investigated how the weight of the objects in a mental model affects spatial belief revision. Can weight override or modulate the LO-principle? Are light objects preferably relocated compared to heavy objects? Or do participants still prefer to relocate the object which is the LO of the inconsistent statement no matter whether it is light or heavy?

Method

Participants. Twenty-nine students from the University of Giessen (18 male; age: $M = 23.34$; $SD = 3.22$) were tested individually. They gave written informed consent and received course credit or were paid at a rate of 8€/hour for their participation.

Materials, design, and procedure. Each participant solved 48 problems. Six practice trials (not analyzed) preceded the experimental trials. Participants received instructions on the computer screen. The structure of the problems was as follows: first, participants received sequentially two statements, also called premises (1, 2), which described the spatial relation between three objects, for example:

- (1) "A is to the left of B"
- (2) "B is to the left of C"

From these two premises, participants were asked to envisage the order of objects, here the three objects are in the arrangement A – B – C. Participants indicated the order they envisaged by choosing one of two arrangements (correct arrangement/correct arrangement mirrored) that were presented on the screen by pressing the corresponding response key (construction phase).

In the next step (inconsistency detection phase), participants were confronted with an additional statement. It was consistent with the initial premises and the arrangement in half of the problems; in the other half it was inconsistent. Participants had to decide whether or not the presented fact was consistent with the model and the premises or not. Here an example for an inconsistent statement: "A is to the right of C". This is the critical point in time where participants had to realize that something must be wrong with their initial mental model of the three objects, not all three statements could be true at the same time. The third statement contradicts the inference from the first two statements. Crucially, participants were told that the third statement is irrefutably true such that they could not ignore the third statement. In cases where participants decided that the fact was inconsistent, they were asked to revise the arrangement, which means that they subsequently chose one out of two revised arrangements presented on the screen by pressing the corresponding button (revision phase). If the first premise is discarded this results in the arrangement B – C – A; if the second premise is discarded this results in the arrangement C – A – B. It is essential to see that the first revision strategy corresponds to the LO-Relocation, whereas the second revision strategy means that the RO is relocated.

To study the effect of object weight the terms, A, B, C were instantiated with the light and heavy objects from Table 1. Further, by integrating a "you" into the problems, we encouraged participants to feel as the agent of the scene and to use an own-body-centered frame of reference (see above; Hauk et al., 2004; Pulvermüller et al., 2005; Willems et al., 2010). We expected that this would foster the perspective taking and that

the participants are therefore even more sensitive to the object properties (see section 2.1).

Here is an example problem:

| | |
|--------------------|--|
| Premise 1: | "The piano is to the left of you." |
| Premise2: | "You are to the left of the curtain." |
| Initial model: | Piano – you – curtain |
| Inconsistent fact: | "The piano is to the right of the curtain." |
| Revised orders: | You – curtain – piano ("relocation of the heavy object") Curtain – piano – you ("relocation of the light object") |

In half of the problems the heavy object was the LO and the light one the RO, in the other half it was reversed. All statements used the spatial relation "left of" and "right of" and were presented sequentially. Positions of the objects (i.e. light and heavy objects in the first, second, and third position) as well as the spatial relations used in the premises ("left of" and "right of"), were counterbalanced across the experiment.

Stimuli were presented and data recorded, using Superlab 4.0 (Cedrus Corporation, San Pedro, CA, 1999-2006). The experiment was run on a custom personal computer (Windows XP) with a standard 19" monitor. Participants provided answers using an RB-530 response box (Cedrus Corporation, San Pedro, CA, 1999-2006). The program recorded (1) the number of correct responses in the "construction" and "inconsistency detection phase", (2) which object (LO or RO) was relocated in the "revision phase", and (3) how much time the participant needed to make the decision.

Results and discussion

Participants selected the correct arrangement in 94% ($SD = 8.11$) of the problems (construction phase). Inconsistencies between the initial information and the contradictory fact were correctly detected in 83% ($SD = 22.74$) of the problems (inconsistency detection phase). Erroneous trials were excluded from further analyses.

ANOVAs with the factors object weight (light vs. heavy) \times functional asymmetry (LO vs. RO) were conducted for the revision choices and the respective revision times. Level of significance was 5%.

Revision choices. ANOVA for revision choices revealed a significant main effect of the LO-RO-asymmetry, $F(1, 26) = 37.17$; $p < .001$; $\eta^2 = .58$. As depicted in figure 1 participants relocated more often the fact's LO ($M = 72\%$, $SD = 21.65$) of an inconsistent fact within a mental model to regain consistency compared to the RO ($M = 27\%$, $SD = 23.96$), $t(27) = 6.41$; $p < .001$, $d_z = 1.21$. All other analyses, both for the main effect of object weight as well as the interaction were non-significant (all $ps > .50$).

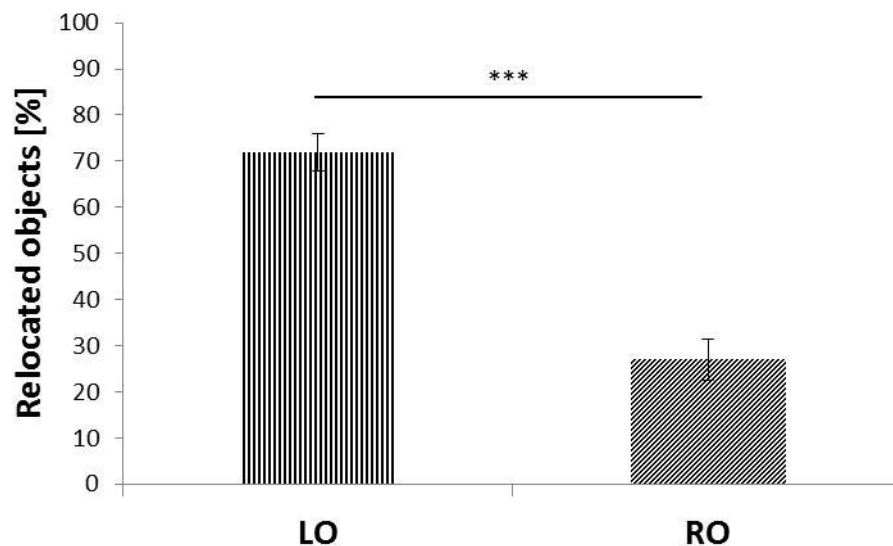


Figure 1. Relative frequency (in %) of model choices based on the relocation of a fact's LO vs. RO in experiment 1 (light vs. heavy objects). Error bars show standard errors.

Revision times. In an ANOVA, none of the differences in the revision times were significant (all $ps > .10$). The results of our first experiment show that participants had a clear preference to relocate a fact's LO compared to the RO in order to regain consistency. This finding has some important theoretical consequences and corroborates our previous results of a strong asymmetry between RO-relocation and LO-relocation (Bucher et al., 2011; Krumnack et al., 2011a; Bucher & Nejasmic, 2012; Knauff et al., 2013; Bucher et al., 2013; Mikheeva et al., 2013; Nejasmic et al., 2014). Particularly, the findings are hard to explain based on abstract, purely propositional representations of spatial relations. If

relations were mentally represented as propositions of the form $r(A, B)$, where A and B are the objects to be located, we should not find an asymmetry between LO and RO. If, however, the participants mentally simulated the relations in a mental model and afterwards revised this model, this might account for the asymmetrical roles the objects play during the processing of spatial relational expressions. In fact, this assumption is supported by several experimental findings. Logan (1994, 1995) showed that if individuals are asked to verify spatial relations in a diagram they shift visual attention to the region where the LO is expected (see also Oberauer & Wilhelm, 2000). Hörnig, Oberauer, and Weidenfeld (2005) explored the integration of new premise information into an existing model and found that people integrate the LO of a relation faster if the RO of the premise was already part of the existing model. In our previous experiments, we were able to show that such directionality effects also play a key role during mental model revision (Bucher et al., 2011; Krumnack et al., 2011a; Bucher & Nejasmic, 2012; Knauff et al., 2013; Bucher et al., 2013; Mikheeva et al., 2013; Nejasmic et al., 2014). Our interpretation was that the RO-LO-asymmetry does not only influence how a model is constructed, but also have an effect when people already have constructed a model and then alter this model to account for newly available information. The findings support the model theory and also corroborate our main assumption that people reason by means of *mental simulations*. These simulations rely on people's actual interaction with the world and so also capture the asymmetries between a scene's reference objects and located objects also know from visual perception (Miller & Johnson-Laird, 1976; Logan, 1994).

The second finding of the experiment, however, is that the preference for LO-relocation is so strong that it could not be overwritten by the weight of the object. Even if the LO was the heavier object, it was relocated preferably. One possible explanation might be that people often have difficulties estimating the weight of an object by just looking at it or imagining it (Charpentier, 1891; Flanagan & Beltzner, 2000; Shim, Carlton, & Kim, 2004; Zhu & Bingham, 2010). However, our pilot study indicates that people are able to discriminate objects, not only in size and movability, but also in weight. Nonetheless, our participants were not inclined to use the type of objects as an indicator for physical effort.

A second possible explanation is that participants did not simulate the weight information, because some of the objects were in any event too heavy to be moved by a single person. The “light” objects were beach towels, sleeping bags, etc. All these objects we carry quite often in our everyday life. However, did you ever plan to move a jukebox or a piano just by yourself? Such items were used as “heavy” objects in our experiment, as they were rated in the pilot study as the heaviest objects. However, our study might indicate that passively rating the weight of an object is different from imagining to move the object. We think that here comes into play that, by integrating a “you” into the problems, we made participants feel as the agent of the scene and to use an own-body-centered frame of reference (see above; Hauk et al., 2004; Pulvermüller et al., 2005; Willems et al., 2010). We expected that this makes participants more sensitive to the object properties. If they were aware of the heaviness of the objects, participants were also likely to realize that the objects were actually too heavy to be moved by one single person. In this case, participants might have ignored the weight and might have also ignored it when they mentally relocated the objects. We think that this is an interesting issue for future research and might even turn into support for the grounded cognition hypothesis. However, in the next experiment we manipulated another object property – size – which might have a stronger effect on the revision choices.

Experiment 2: small vs. large objects

Method

Participants. A new sample of 21 students from the University of Giessen (nine male; age: $M = 22.86$; $SD = 5.27$) were tested individually. They gave written informed consent and received course credits for their participation.

Materials, design, and procedure. The instructions on the computer screen and the procedure were the same as in experiment 1, with the difference that the objects used were small and large objects instead of light and heavy objects. Accordingly, the manipulated factors serving as independent within subject factors are: object size (small vs.

large objects) and functional asymmetry (LO vs. RO). The same dependent variables as in experiment 1 were of interest.

Results and discussion

Mean percentage rate of correctly constructed models was 98% ($SD = 2.15$, construction phase) and in 94% ($SD = 8.54$) of the inconsistent problems participants correctly identified the inconsistency between the initial model and the contradictory fact (inconsistency detection phase). Erroneous trials were excluded from further analyses. ANOVAs with the factors object size (small vs. large) \times functional asymmetry (LO vs. RO) were conducted for the revision choice and the revision times, respectively. Level of significance was 5%.

Revision choices. The ANOVA for revision choices revealed significant main effects of object size, $F(1, 20) = 5.75$; $p = .026$; $\eta^2 = .22$ and functional asymmetry, $F(1, 20) = 63$; $p < .001$; $\eta^2 = .76$, (see figure 2; the interaction was non-significant, $p > .24$). Additional t -tests revealed that small objects ($M = 54\%$, $SD = 14.57$) were more often relocated than large objects ($M = 46\%$, $SD = 12.25$), $t(20) = 2.39$; $p = .026$, $d_z = 0.52$ (see Fig. 1) whereby LOs were still significantly more often relocated ($M = 80\%$, $SD = 24.66$) than ROs ($M = 20\%$, $SD = 15.91$), $t(20) = 7.91$; $p < .001$, $d_z = 1.73$.

Revision times. Results of the ANOVA for revision times were non-significant (all $ps > .15$).

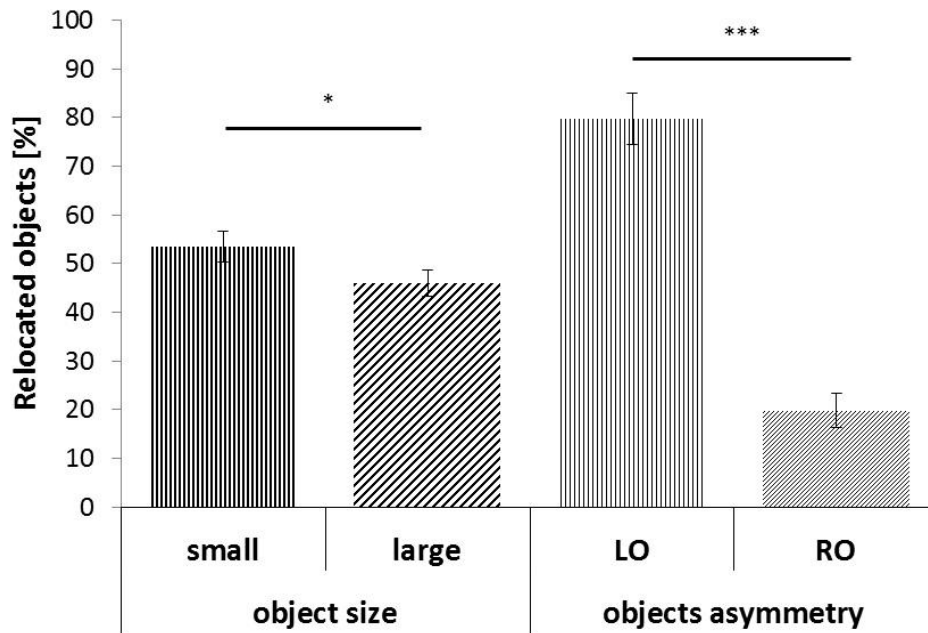


Figure 2. Relative frequency (in %) of model choices based on the relocation of small and large objects, as well as of LO and RO in experiment 2. Error bars show standard errors.

Experiment 2 shows that the physical size of objects had an effect on how people revised their existing belief about the arrangement of objects in space. Participants relocated small objects more often than large objects. The finding echoes what would be found in the physical world where small objects are more often transferred from one location to the other while large objects (like buildings) remain stationary. This finding agrees with the grounded cognition approach and is more difficult to explain based on purely symbolic cognitive theories. The finding also agrees with the mental model theory of reasoning, in which people reason spatially by constructing, inspecting, and varying spatial mental models that mirror the situation described in the premises (Knauff, Rauh, & Schlieder, 1995; Ragni et al., 2005; Rauh et al., 2005; Nejasmic et al., 2011). If such a model is then contradicted by a new fact, people try to revise the model by local transformations within this model. Results from the second experiment support the assumption that these mental operations are affected by the imagined size of objects. The underlying mechanism is most likely a mental simulation of the act of relocation, resulting in the preference to relocate small objects more often than large objects. In fact, the big

objects such as railway stations or bridges used in this experiment are hardly ever relocated in real life while vases, monitors, and lamps are often relocated.

With the next experiment, we tried to replicate this effect with objects which were rated in the pilot study as movable or immovable. The question is again: does object property affect reasoning and belief revision? Is the physical challenge related to an immovable object somehow reflected when we manipulate it mentally?

Experiment 3: movable vs. immovable objects

Method

Participants. A new sample of 27 students from the University of Giessen (five male; age: $M = 22.81$; $SD = 6.29$) were tested individually. They gave written informed consent and received course credit for their participation. Data from one participant were excluded due to a technical problem.

Materials, procedure, and design. The instructions on the computer screen and the procedure were the same as in experiment 1 and 2. Again, we manipulated two factors within this experiment: object movability (movable vs. immovable; see table 1) and functional asymmetry (LO vs. RO) as the independent within subject factors. The same dependent variables as previously were of interest.

Results and discussion

Participants selected correct arrangements in 97%, ($SD = 3.99$) of the cases (construction phase). They detected inconsistencies (inconsistency detection phase) between the initially constructed arrangements and the contradictory facts in 89% ($SD = 19.24$), correctly. Erroneous trials were excluded from further analyses.

ANOVAs with the factors object movability (movable vs. immovable objects) \times functional asymmetry (LO vs. RO) were conducted for the revision choices and the respective revision times. Level of significance was 5%.

Revision choices. In this experiment, the ANOVA for revision choices again revealed a significant main effect of functional asymmetry, $F(1, 24) = 120.60$; $p < .001$; η^2

= .83. Participants regained consistency more often by relocating the fact's LO ($M = 84\%$, $SD = 18.24$), compared to the relocation of a fact's RO ($M = 20\%$, $SD = 3.99$), $t(24) = 10.98$; $p < .001$, $d_z = 2.19$. In the revision choices, the differences between objects which are movable or immovable and the interaction were non-significant ($ps > .25$).

Revision times. The ANOVA for revision times revealed a marginal significant main effect of object movability, $F(1, 10) = 3.80$; $p = .080$; $\eta^2 = .28$. A two-tailed t -test revealed that revision times were lower for revisions based on relocations of movable objects ($M = 2878.11$ ms, $SD = 1192.19$) compared to immovable objects ($M = 5302.12$ ms, $SD = 5785.98$), $t(25) = -2.45$; $p < .027$, $d_z = 0.46$, (see figure 3). In addition, ANOVA revealed a marginal main effect of functional asymmetry, $F(1, 10) = 3.75$; $p = .082$; $\eta^2 = .27$ but subsequent analyses as well as the interaction were non-significant (all $ps > .10$).

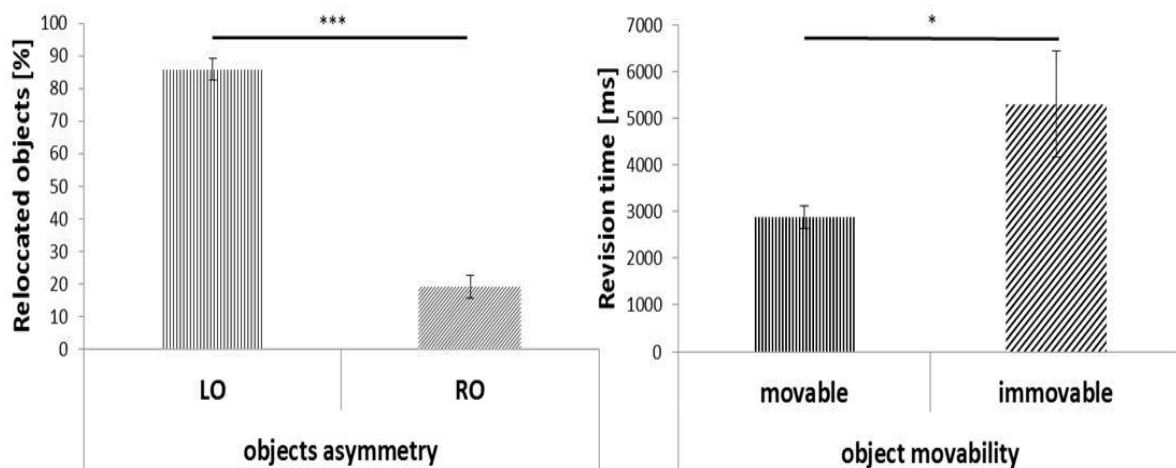


Figure 3. Relative frequency (in %) of model choices based on the relocation of a fact's LO vs. RO and revision times (in ms) based on the relocation of movable or immovable objects in experiment 3. Error bars show standard errors.

The results of experiment 3 demonstrate that participants did not prefer to relocate movable objects compared to immovable objects, but revision times differed significantly depending on the objects' movability. Participants needed less time to establish consistency between the initial premises and the fact, when the revision was based on a relocation of a movable object. This is what would also be expected when real objects in the physical world would be subject to manipulation. For instance, it is possible to relocate

ovens, but it is more time consuming to move an oven than a wheelchair. Thus, participants needed less time to mentally “push” and relocate vehicles than relocating heavy ovens. This finding agrees with studies on the effects of mental motion on human reasoning and perception (Matlock, 2004; Richardson & Matlock, 2007) and with studies showing that a mental manipulation of objects is more time consuming if they are also harder to be moved physically (Flusberg & Boroditsky, 2011).

Overall mixed model analysis

We reported three experiments showing that different object properties have effects on different independent variables. In experiment 1, we did not find reliable differences in revision preference and duration between light and heavy objects. The imagined weight of the manipulated objects did not affect the LO-preference. In experiment 2, we found that the size of objects indeed affects the revision choice. Smaller objects were more often relocated than larger objects, what agrees with the grounded cognition hypothesis. But, we did not find reliable difference in the revision times. In experiment 3, the pattern of results in revision choices and revision duration was reversed. Here, movability had an effect on revision duration but not on objects choices.

So far, we did not treat the experiments as a single study in order to exclude a possible crosstalk of the used object properties. However, the three experiments differed only regarding the type of objects (light vs. heavy, small vs. large, movable vs. immovable) and samples of participants. Therefore, we submitted the data to an overall analysis and computed additional ANOVAs. For the construction an inconsistency detection phase, ANOVAs were conducted with the three experiments as an independent variable and correct decisions as dependent variables, respectively. The ANOVA for the construction phase revealed a significant effect, $F(2, 73) = 3.65$; $p = .031$. Subsequent t -tests revealed that significantly more correct models were constructed in cases where small and large objects were used, compared to light/heavy $t(33.2) = 2.76$; $p = .009$, $d = -0.78$, and movable/immovable objects $t(39.7) = 2.27$; $p = .028$, $d = -0.60$. The error rates of the

inconsistency detection phases do not differ between the experiments $F(2, 73) = 1.49; p = .231$.

Two additional ANOVAs were conducted with the factors objects' property (weight, size, movability) and the three experiments (1, 2, 3) as independent variables and the revision choice and the revision duration as dependent variables. In this way, it is possible to evaluate, whether different object properties would have different effects on different dependent variables, that is, revision choice and revision duration.

Revision choices. The ANOVA for revision choices revealed a significant main effect of objects' property, $F(1, 73) = 4.52; p = .037; \eta^2 = .06$. Participants regained consistency more often by relocating objects with “more advantageous” properties (light, small, or movable; $M = 52\%$, $SD = 14.63$), compared to “objects with “more disadvantageous” properties (heavy, large, immovable; $M = 48\%$, $SD = 14.63$). The interaction was non-significant ($p = .49$).

Revision times. The ANOVA for revision times revealed a marginal significant interaction of objects' property \times experiment, $F(2, 74) = 3.04; p = .054; \eta^2 = .08$. Subsequent one-tailed t -tests revealed significant lower revision durations for movable objects compared to light $t(34) = -2.07; p = .023, d = 0.52$, and small objects $t(22) = 1.64; p = .058, d = 0.54$ (for an overview, see table 2). In contrast, revision durations did not differ, for neither, immovable objects compared to heavy, nor to large objects (all $ps > .22$).

Table 2
Descriptive statistics of relative frequencies (RF in %) and respective revision times (RT in s) for the different object properties in experiment 1-3 with corresponding standard errors (SE)

| | Object properties | | | | | |
|--------|-------------------|----------|----------|----------|----------|-----------|
| | light | heavy | small | large | movable | immovable |
| RF(SE) | 51(3.4) | 49(2.4) | 54(3.2) | 46(2.7) | 50(2.5) | 50(2.5) |
| RT(SE) | 7.1(2.0) | 4.3(.75) | 5.3(2.4) | 5.9(2.0) | 2.7(.36) | 5.1(1.3) |

The analyses show for revision choices that all objects that are supposed to be classified as “in general more movable” or advantageous, either by a lower weight, by a

smaller size, or by an increased movability, are relocated preferably, compared to the disadvantageous ones. In addition, taking a deeper look on these advantageous objects, the analyses show that the inherent motion of an object facilitates the relocation process compared to other advantageous objects resulting in lower revision times.

General discussion

We reported three experiments on the connection of spatial belief revision and grounded cognition. We showed that spatial belief revision is sensitive (1) to the functional asymmetry between the reference object (RO) and the located object (LO) and also (2) to some (but not all) physical object properties. These results show that linguistic aspects and “embodied aspects” can interact if people revise an existing model in the light of new information. In the following we discuss both findings and draw some general conclusions on grounded spatial belief revision.

The finding that people have a strong tendency to relocate the LO rather than the RO agrees with previous findings (Bucher et al., 2011; Krumnack et al., 2011a; Bucher & Nejasmic, 2012; Knauff et al., 2013; Bucher et al., 2013; Mikheeva et al., 2013; Nejasmic et al., 2014). It also agrees with theories suggesting a strong link between thought processes and language (Clark, 1969, Polk & Newell, 1995). According to this theory each object in a spatial sentence plays a specific role and this might affect whether people are more inclined to relocate it or to keep it at its initial position. Basically, this theory states that functional relations, like the abstract subject-predicate relation that underlies sentences, do affect how humans reason, and, more precisely, also might influence how they revise an initial model (Clark, 1969, Polk & Newell, 1995). Our findings agree with this theory as participants seem to interpret the RO as more stationary whereas the LO is seen as more flexible. As a result, the LO-principle is the major revision principle applied by participants in all of our experiments. The result is robust and also appeared in previous experiments (Bucher et al., 2011; Krumnack et al., 2011a; Bucher & Nejasmic, 2012; Knauff et al., 2013; Bucher et al., 2013; Mikheeva et al., 2013; Nejasmic et al., 2014).

Moreover, our results support the assumption, that spatial belief revision includes a mental simulation of the asymmetry between a scenes reference object and located object.

According to the idea of grounded cognition, the mind is embodied, and thus cognitive processes must be grounded in perceptual, motoric, or emotional experience (for an overview, see de Vega et al., 2008). From this point of view, human thinking is based on perceptual simulations and modality-specific representations (Barsalou, 2008, 2010) and thus, we expected that object properties might influence how humans revise mentally spatial arrangements. To cope with the problem that properties are naturally correlated in objects, we disentangled them by experimental means and our results suggest that we were successful in doing so. This enables us to show for the first time that different object properties have different effects on spatial belief revision processes. Overall, the LO-principle is so strong that it is seldom overwritten by the imagined physical properties of the objects in the model. However, some object properties are more able to reduce the LO-preference while others are not.

Our findings also show that different psychological measures are sensitive to the effects of different objects properties. On the one hand, size affected the frequency with which objects were mentally relocated, and thus participants preferably changed the position of small objects, whereby large objects were left in the same position. What happens when we transfer this result to the physical world? It basically means that a vase is relocated preferably to a house. That makes sense, given that we indeed relocate vases more often and more easily than houses. On the other hand, movability modulated the time individuals needed for the revision process. If movable objects were relocated, participants needed less time compared to immovable objects. This also agrees with real actions in the physical world and previous experimental findings (e.g. Flusberg & Boroditsky, 2011). Every-day experiences show that it is more time consuming to move an oven than a wheelchair. In this sense participants needed more time relocating stationary ovens than mentally “pushing” the wheelchair.

In almost the same manner we assumed that, for instance, a beach towel as a light object would be preferably or faster relocated than a jukebox or a piano (used as heavy

objects in the experiment). But we did not find such an influence of objects' weight on our revision problems. While size and movability showed effects, it seems puzzling that weight did not. In the following, we discuss some possible reasons. One possible explanation is that participants in our experiments successfully simulated the weight information but did not take them into account for the revision process because the objects were too heavy to be relocated by one person where the first-person perspective was explicitly triggered by the experimental procedure. A second possible reason is related to recent studies, suggesting that the effects of "embodiment" on human reasoning and perception are probably based on experimental demand characteristics, i.e. that participants are aware of the experimenters' intention.

For instance, some studies report that the fact to wear a heavy backpack might directly influence how humans perceive slopes and distances. In the studies the task was to estimate distances and slopes and the results show that participants overestimate them when wearing a heavy backpack. Such findings indicate that participants are subconsciously influenced by the weight of the backpack (Bhalla & Proffitt, 1999; Proffitt, Stefanucci, Banton, & Epstein, 2003; Proffitt, 2006). Nonetheless, there are also counter examples indicating that in such experimental settings participants were aware of the experimenters' intentions and shaped their answers accordingly (Durgin et al., 2009). Yet, in the present experiments it is unlikely that participants could guess the experimenters' intention, because the experimental variation was rather subtle and less obvious than in other studies (and our instruction was more neutral). In addition, we observed LO modulating effects of size and movability.

Thus, a further possible explanation is motivated by studies suggesting that weight as an object property, is not simulated during reasoning. The argumentation is that humans have a hard time estimating the weight of an object by just looking or imagining it (Flanagan & Beltzner, 2000; Zhu & Bingham, 2010); despite their doubtless capability of deliberately discriminating object properties, as e.g. shown in the pilot-study where our participants were explicitly asked to estimate the size, movability, and the weight of a given object. However, the processing of the respective object characteristics during

reasoning tasks, as required in the main experiment might involve more subtle cognitive processes which explains why weight did not influence spatial belief revision. The assumption is related to the LASS (linguistic and situated simulation) theory of conceptual processing (Barsalou, Santos, Simmons, & Wilson, 2008). During recognition of a presented word, the linguistic system activates correlated simulations in the brain's modal system. Based on this simulation, not only the general meaning of the processed word is represented but rather situated experiences are simulated, preparing agents for possible actions in particular situations. This is in line with the assumption that language comprehension involves perceptual simulations of a described scene, including a mental activation of possible actions a person can realize with the mentioned objects (Glenberg & Robertson, 1999; Kaschak & Glenberg, 2000).

An important aspect in this context is that it seems to matter in what modality humans experience object properties. Simulations are supposed to be executed in the same brain areas that are also used for actually perceiving certain properties. Evidence is e.g. provided by studies using verification tasks, where humans are found to be faster and more accurate when a property is presented with a congruent object, i.e. an object sharing the same property as compared to an incongruent object (featuring a property that does not match the target objects property) (Spence, Nicholls, & Driver, 2001; Pecher, Zeelenberg, & Barsalou, 2003, 2004). In our experiments, simulations might have been strongest for properties according to which objects are easy to be judged from visual input: the size of an object is very directly visually perceivable, while the movability of an object is more subject to inference from other object features (e.g. has wheels). The weight of an object definitely needs to be inferred from its further characteristics. Observers appear to use an "indirect route" when estimating the weight of objects. They tend to infer the object's weight from the (directly estimated) velocity by which an object can be lifted, or they use the effort that it takes to lift it as a reference point for their weight estimation (Shim, Carlton, & Kim, 2004). For participants in our weight experiment, an indirect route – for instance via the estimation of the objects' size - was not accessible (since size was kept constant across light and heavy objects). Additionally, whereby everyone has experienced

not less than once how large a church might be, or how a wheelchair is relocated, exceedingly few people might have experienced how difficult it is to relocate a piano. It seems plausible that as a consequence, weight was not found to alter the LO-principle, whereas this null effect regarding weight does not contradict grounded cognition assumptions.

In point of fact, our findings create new conceptions between grounded cognition and mental models. Today, the vast majority of researchers consider the mental model theory to be the empirically best supported theory of human spatial inference (Vandierendonck, Dierckx, & de Vooght, 2004; Goodwin & Johnson-Laird, 2005; Knauff, 2009, 2013; for an exception see: van der Henst, 2002). The present work shows that the idea of a mental simulation in mental models can also incorporate other physical features and that these features influence human reasoning as shown here in the case of spatial belief revision. In fact, the theory of grounded cognition and the theory of mental models make a good match. In particular, the mental models theory assumes that we reason using mental simulations, and infer from simulations what might be the case in a certain situation. The present study followed the question whether object properties influence the way how humans revise their beliefs about spatial relations and results show that objects with more advantageous properties (light, small, and movable) are relocated preferably or faster (movable objects) over more disadvantageous objects (heavy, large, and immovable). More precisely, objects that suggest a motion like bicycles or wheelchairs are faster relocated than immovable objects like counters or stoves. These findings support the idea that people also consider their knowledge about physical objects properties during spatial belief revision.

We summarize, that spatial belief revision can be influenced by object characteristics that are mentally represented. An important corollary from our study is that different object properties are not considered in the same manner for spatial belief revision. In fact, different object properties have different effects on grounded spatial belief revision. This is a novel finding and opens up new avenues of research on how humans mentally simulate actions with imagined physical objects during reasoning.

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Chapter 7

Neuronal correlates of
spatial belief revision

Abstract

Spatial belief revision is required when reasoners are confronted with undisputed new information that has to be taken into account. Spatial belief revision is described as a variation of initially constructed mental models according to the functional asymmetry between reference objects (RO) and the located objects (LO) of binary spatial relations. Humans show a preference to relocate a LO of the inconsistent statement within a mental model in order to regain consistencies. In an event-related fMRI study we investigated neuronal correlates of underlying cognitive processes. As a first step towards investigations of spatial belief revision, the present study focuses mainly on the inconsistency detection and mental model variation process. To work out neuronal correlates of spatial belief revision 22 participants were tested in a 1.5-T whole-body magnetic resonance tomograph (Siemens Symphony). Brain activity elicited during the revision process was contrasted with neuronal activity during the maintenance of object arrangements in working memory. Results of the present fMRI study underpin the assumption that the revision processes is a local transformation of mentally represented objects. Spatial belief revision leads into neuronal activation in the dorsolateral frontal gyrus, pre- and postcentral gyri, with the supplementary motor area, superior and inferior parietal lobes (supramarginal and angular gyri), the lingual, fusiform and inferior temporal gyri, putamen, insula and thalamus.

Introduction

In everyday life, humans deal with all sorts of information, originating from a variety of sources. Information as well as the information sources vary regarding the degree of trustworthiness, reliability, concreteness, completeness, familiarity, and much more. Reasoners inevitably form beliefs based on the input they receive, although frequently, things turn out to be different from what a reasoner was at first inclined to believe. As a consequence, beliefs often have to be adjusted, in the light of additional information, and sometimes undergo thorough revision. For instance, when an incontrovertible fact contradicts what was initially believed to be true. In this case, belief revision is the means that allows regaining consistency within sets of beliefs.

Recently, psychological studies on spatial and relational belief revision have been conducted by our research group. The studies used behavioral experiments and computational modeling to approach - for example - the following questions: how do humans represent spatial beliefs, for instance beliefs about the spatial arrangement of objects in a room? What are prerequisites to enable spatial belief revision? What are guiding factors of spatial belief revision? Are there preferred strategies applied by reasoners when revising spatial beliefs? (Bucher, Krumnack, Nejasmic, & Knauff, 2011; Krumnack, Bucher, Nejasmic, & Knauff, 2011; Bucher & Nejasmic, 2012; Bucher, Nejasmic, Bertleff, & Knauff, 2013; Knauff, Bucher, Krumnack, & Nejasmic, 2013; Mikheeva, Bucher, Nejasmic, & Knauff, 2013; Nejasmic, Bucher, & Knauff, 2013; Bucher & Thorn, 2014; Nejasmic, Bucher, Thorn, & Knauff, 2014, Nejasmic, Bucher, & Knauff, under review).

With the current study, we intend to uncover the neuronal substrate of spatial belief revision. Knowing which structures of the brain support performance of a certain task is highly informative about the cognitive processes involved to solve the task. The aim is to specify the precise nature of the underlying cognitive mechanisms in spatial belief revision.

Our study is based on assumptions made by the mental model theory (MMT; e.g. Johnson-Laird, 1983; Johnson-Laird & Byrne, 1991; Goodwin & Johnson-Laird, 2005). The MMT is the leading theory, when human thinking and reasoning is explained. Three distinct but interrelated phases of thought are suggested: the construction, the inspection, and the manipulation of mental models. Mental models are constructed, using previously given information. Consistently, spatial beliefs are represented in spatial mental models, using previously given spatial information. Confronted with a statement (or any piece of information), the model can be easily inspected for consistency with the statement (e.g. Johnson-Laird, Girotto, & Legrenzi, 2004). If the statement is found to be consistent with the initially constructed model, the reasoner can easily accept the initially constructed model as the final model. However, in cases where inconsistencies are detected, the model will undergo revision. Especially, in cases where the inconsistent piece of information is

incontrovertibly true, the reasoner most likely feels inclined to take the fact into account and revise the initially constructed model accordingly.

The experimental paradigm, we used for our study follows the suggested tripartite structure of reasoning with mental models. Our participants received information conveyed by two premises and were asked to imagine the spatial arrangement of objects, described by these premises. This first step of the experimental task, thus, represents the “active” construction of a spatial mental model. In a next step, participants received a third premise, introduced as an incontrovertible fact that has to be taken into account (while the instruction informed participants that the first two premises are not necessarily true). This second step requires inspection of the mental model. The third step is the most interesting for our study of belief revision. Here, participants revise their initially constructed model, given inconsistency of the fact with the model has been successfully detected during the second phase.

We aimed to disentangle the belief revision process from the maintenance of information in working memory. Hence, we established two conditions: in half of the 48 presented problems, the fact was consistent with the two premises presented in the problem description, i.e. the fact confirmed the initially constructed model. Here, the task of the participant was simply to maintain the model in working memory (maintenance condition). In the remaining half of the problems, the fact was inconsistent with the constructed model, requiring the participant to revise the model accordingly (revision condition). We used an event-related design, allowing us to examine brain activity elicited during construction and revision (or maintenance, respectively).

Construction phase

Imagine you work your first day in a supermarket and your new colleague explains you the layout of the fruit sales booth. She provides you with the following spatial description:

“The apples are to the left of the mangos.”

“The mangos are to the left of the kiwis.”

Not directly standing in front of the fruit sales booth, you come up with a mental representation of the information conveyed by the description. Most likely, you represent the fruit arrangement in a compressed format, integrating all pieces of information into one spatial mental model, i.e.: Apples – Mangos – Kiwis (Johnson-Laird, 1983; Johnson-Laird & Byrne, 1991; Knauff, Rauh, & Schlieder 1995; Vandierendonck & de Vooght, 1997; Knauff, Rauh, Schlieder, & Strube, 1998; Schaeken, Girotto, & Johnson-Laird, 1998; Goodwin & Johnson-Laird, 2005; Ragni, Knauff, & Nebel, 2005; Rauh, Hagen, Kuss, Knauff, Schlieder, & Strube, 2005; Nejasmic, Krumnack, Bucher, & Knauff, 2011; Nejasmic, Bucher, & Knauff, in press).

It is assumed that the neuronal correlates of active construction are found in the parietal cortex. The parietal cortex is associated with spatial abilities and spatial processing (e.g. Watanabe et al., 2004). In particular, the posterior part of the parietal cortex has been found to play a crucial role in spatial working memory. Activity has especially been found to be persistent in tasks requiring maintenance of positional information, in order to be available for a later use of guiding behavior (Culham et al., 1998; Awh et al., 1999; Wojciulik, & Kanwisher, 1999; Corbetta, Kincade, Ollinger, McAvoy, & Shulman, 2000; Hopfinger, Buonocore, & Mangun, 2000; Knauff, Kassubek, Mulack, & Greenlee, 2000; Nobre, Gitelman, Dias, & Mesulam, 2000; Knauff, Fangmeier, Ruff, & Johnson-Laird, 2003; Ruff, Knauff, Fangmeier, & Spreer, 2003; Curtis, 2006; Monti, Parsons, Martinez, & Osherson, 2007).

The first step in our spatial belief revision paradigm requires “active” construction of spatial arrangements, just like in the example above. In an fMRI study by Fangmeier and colleagues, a similar “active construction” task was completed by the participants, and the performance in the construction task was contrasted to performance in a maintenance task where participants simply had to hold the letters in memory (Fangmeier, Knauff, Ruff, & Sloutsky, 2006). This procedure enabled to differentiate between premise processing (maintaining premise information) and incrementally integration of given information into a model (construction). For premise processing mainly a temporo-occipital-network was

active, a network that is associated with the visual working memory and imagery (Kosslyn, Ganis, & Thompson, 2001). Knauff (2009) refers, based on this neuronal finding, to the cognitive process of premise processing as the “visual image construction”. The occipital lobe is at this stage involved in premise processing in a way that a visual mental image is formed on the basis of given information, together with general knowledge about the specific situation. Although neuronal activity in the temporal region is often associated with linguistic processes (Goel, Buchel, Frith, & Dolan, 2000; Ferstl, 2007; Ferstl, Neumann, Bogler, & von Cramon, 2008), in the current context, the activity might reflect the involvement of general knowledge about the entities mentally maintained in working memory. When premise information is integrated into a model, neuronal activity seems to shift to the anterior prefrontal cortex, a brain region associated with reasoning, relational processing and relational integration (Knauff et al, 2003; Ruff et al., 2003; Fangmeier et al., 2006; Monti, Parsons, & Osherson, 2009). The integration of information has also been termed “image-to-model transformation”, where the previously formed mental image is translated into a more abstract spatial mental representation in the sense of a mental model (e.g. Johnson-Laird, 1983). The mental model, in turn, forms the basis for subsequent inferences (Knauff, 2009).

Inconsistency detection and Revision

After a mental model is successfully constructed it is possible to infer new pieces of information that has not been explicitly given by the premises. It is assumed that humans do so by maintaining and inspecting the mental model. The inspection of a model allows a reasoner to infer conclusions, confirm valid conclusions, and – in the context of the present study of particular interest - to detect inconsistencies between newly given, pieces of information and the model. This “mental model processing” (Knauff, 2009) has found to activate the posterior parietal cortex and the dorsolateral prefrontal cortex. The more relations are processed, i.e. the more complex a task, the more neuronal activation has been found in these regions (Halford, Wilson, & Phillips, 1998; Fangmeier et al., 2006; Knauff, 2009). On this basis it is realistic to anticipate that the mental model processing contains

two important brain regions: the mental model is processed including parts of the parietal cortex, whereby higher cognitive processes like the inspection or manipulation of such a mental model are realized by including the prefrontal cortex. Drawing on our above sales manager example, you would at this stage be able to reproduce all explicit given relations (e.g. that the apples are to the left of the mangos), although you might not remember the exact wording of the premises (Mani & Johnson-Laird, 1982). Additionally, you are most likely able to infer the implicitly given relation of the apples to the kiwis (which is on the left). Let's extend our example to a case of belief revision: imagine you are on your way to the fruit sales booth when you meet the branch manager who tells you that the kiwis are to the left of the apples. Confronted with this additional statement, and given you consider it to be true, you have to change your previous beliefs about the fruit arrangement.

Since inconsistency detection has been proposed to result from the detection of a conflict that arises when a new piece of information contradicts an existing belief (Johnson-Laird, Legrenzi, & Girotto, 2004), it might be related in a broader sense to work done in the field of error detection during reasoning. The anterior cingulate cortex is ascribed to play a crucial role in conflict monitoring and error detection, especially when humans are confronted with tasks that require executive control of cognitive processes like the selective attention, information processing in working memory, and language generation (Dehaene, Posner, & Tucker, 1994; van Veen & Carter, 2002; Botvinick, Cohen, & Carter, 2004; Yeung, Botvinick, & Cohen, 2004; Oliveira, McDonald, & Goodman, 2007).

Most studies on spatial belief revision have been conducted with verbal stimulus material, presenting premises in the form of binary relations $r(X,Y)$. One of the main findings is that the revision process is sensitive to some sort of functional asymmetry of objects presented in a statement such as "A is right of C". In this statement, object "A" serves as the "located object" (LO) while object "C" serves as the "reference object" (RO). Many studies have shown that given an initially constructed model ABC, consistency with the (inconsistent) fact "A right of C" is preferably achieved by relocation of the LO "A", resulting in the revised model BCA, while reasoners relocate the RO "C" in only a small

percentage of the cases. The “LO-effect” has been shown to be robust and strong (actually occurring in 80-90% of revisions of the here described type) (Bucher, et al., 2011; Krumnack, et al., 2011; Bucher & Nejasmic, 2012; Bucher, et al., 2013; Knauff, et al., 2013; Mikheeva, et al., 2013; Nejasmic, et al., 2013; Bucher & Thorn, 2014; Nejasmic, et al., 2014, Nejasmic, et al., under review).

The reason for the LO preference has been explained by the subjectively perceived differences in the flexibility of the objects. While the RO’s spatial position appears to be more specified and fixed, the LO seems to be the more flexible and locatable (Miller & Johnson-Laird, 1976; Talmy, 1983; Landau & Jackendoff, 1993; Tenbrink, Andonova, & Coventry, 2011). Interestingly, the LO effect can be modulated by the properties of objects. A recent study, conducted by our group, showed that size of the objects matters when reasoners mentally relocate objects within arrangements. Small objects such as lamps were preferably relocated mentally as opposed to big objects (such as bridges). Also, objects that are - from physical experiences and by interaction with objects - known to be easier to move (e.g. bicycles), compared to objects that are more difficult to move (such as ovens) influenced the mental relocation process. In accordance with what you would expect in a physical setting, the “easy to move” objects were relocated faster than the “difficult to move” objects (Nejasmic et al., 2013; under review).

These findings are actually in line with the idea of grounded cognition. An approach where it is assumed that the process of thought is a mental simulation of bodily experiences. It is assumed, for instance, that reading a word that represents a specific action and movement is sufficient to elicit activation of the motoric system (Glenberg & Robertson, 1999; Glenberg & Kaschak, 2002; Kaschak & Glenberg, 2000; Rinck & Bower, 2004; Bergen & Chan, 2005; Pulvermüller, 2005).

Based on these findings and the grounded cognition approach, we assume that mental transformations necessary for spatial belief revision are describable as mental simulation of an actual action, in that case a relocation of an object from one position within an arrangement to a new one. Activations in a parieto-fronto-central network (including the supramarginal gyrus, inferior and superior parietal lobules, and sensory

cortex of the parietal lobes, the supplementary motor area, and the premotor regions of the frontal lobes) are associated with action-related language processing (Esopenko et al., 2012).

To work out neuronal correlates of spatial belief revision we contrast brain activity elicited during the revision process with neuronal activity during the maintenance of object arrangements in working memory. This method was already used in studies investigating reasoning processes (Ruff et al., 2003; Fangmeier et al., 2006). Confronted with either a valid conclusion or an inconsistent fact, for both, it is assumed that the previously constructed mental model is inspected in order to infer an implicitly represented relation. However, tasks of the maintenance condition do not require a manipulation and variation of the initially constructed model, while tasks of the revision condition do require a mental relocation. Accordingly, we should be able to find neuronal activity in different cortical brain regions, for the maintenance and the revision condition, respectively.

We assume that inconsistency detection is performed by inspection of previously constructed mental models, while belief revision is based on model variation. We aim to identify common and distinct brain areas involved in these processes. Regions expected to be involved in spatial belief revision are the parietal lobes, presumably involved in encoding spatial information (e.g. Mellet et al., 1996) and reasoning (e.g. Knauff & Johnson-Laird, 2002; Ruff et al., 2003; Knauff et al., 2003; Knauff, 2009), and frontal structures that are involved in executive functions.

To sum up, the revision process might be correlated with neuronal activity in regions relevant for mental model processing and manipulation like for instance the posterior parietal cortex and the dorsolateral prefrontal cortex (Mellet et al., 1996; Ruff, et al., 2003; Fangmeier et al., 2006), whereby additionally brain regions related to error monitoring are expected to be involved.

Method

Participants

Twenty-two right-handed healthy participants (11 male; age: $M = 24.64$; $SD = 4.07$) were tested individually and received 8€/h for participation. All subjects were students from the University of Giessen, reported normal or corrected-to normal visual acuity. None reported a history of neurological or psychiatric disorders. Data from one participant were not recorded due to a technical problem. The study was approved by the local ethics committee (local ethics commission, Department of Psychology and Sports Science, University of Giessen), and all participants gave their informed written consent in accordance with the Declaration of Helsinki. The experimental setting, especially the presentation duration of the stimulus material (to ensure that participants go through all the stages of the reasoning process) was carefully evaluated in a pre-study conducted prior to the fMRI study. Ten right-handed healthy subjects (3 male; age: $M = 26.40$; $SD = 4.40$) were tested outside the scanner. They were tested individually and received 8€/h for participation. All 10 participants of the pre-study were also students from the University of Giessen, gave their informed written consent, reported normal or corrected-to normal visual acuity no history of neurological or psychiatric disorders.

Stimulus material, and stimuli presentation, and procedure

Each participant solved 48 problems and eight practice trials (not analyzed). Participants received task instruction in written form on a paper. The structure of the problems was as follows: two premises (1, 2) were presented sequentially describing the relation between three objects, resulting in an one-dimensional linear arrangement. Small, equal-sized, and disyllabic-termed objects were used belonging to either the category “fruit” or “tool”, for example:

- (1) “apple left of pear”
- (2) “pear left of kiwi”

From these premises 1 and 2, the spatial arrangement apple – pear – kiwi follows. The task was to construct the correct arrangement. To ensure that this experimental step

was accomplished correctly by the participant, the correct arrangement was shown on the screen. In the next, and in this experiment, crucial step, participants were confronted with an additional statement, the fact. Half of the problems constituted the “maintenance condition”. Hence, in half of the problems, the fact was consistent with the initial description conveyed by premise 1 and 2. The other half of the problems constituted the “revision condition”. Hence, in these problems, the fact was inconsistent with parts of the description. Accordingly, the fact called for a revision of the initially constructed arrangement. Participants were told that the third statement is irrefutably true so they could not ignore inconsistencies, while the premises 1 and 2 may not be true. The problems of the maintenance condition, where the fact confirmed previous information, simply required the participants to remember the initially constructed arrangements. In contrast, in the revision condition participants were asked to revise the initial arrangement such that it coheres with the fact. Participants indicated their solutions with the right hand in a two-alternative-forced choice via button press on a small touch input device, with the index or second finger, respectively. Two arrangements, the initial arrangement and the initial arrangement mirrored were presented as possible choices in the maintenance condition. In the revision condition, the revised arrangement and the revised arrangement mirrored were presented as choice alternatives. Given that reasoners clearly prefer to relocate LOs, the LO revision was presented as correct revision solution. Figure 1 illustrates an example of a revision problem (top) and a maintenance problem (bottom).

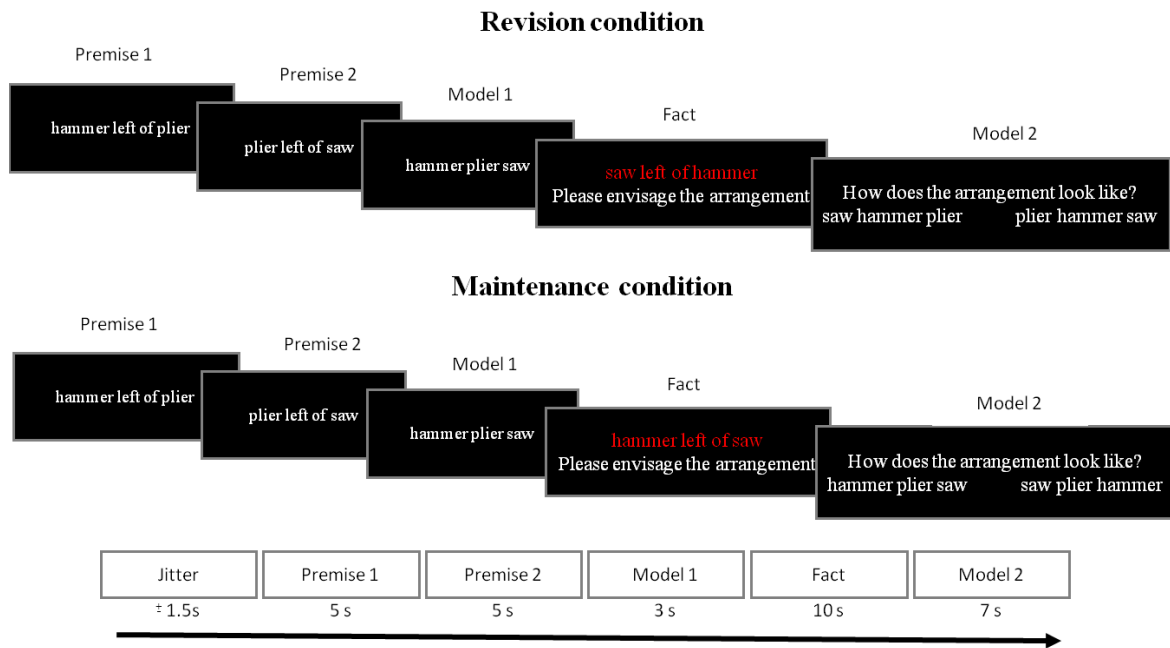


Figure 1. The Revision and the Maintenance condition exemplarily depicted with objects from the “tool” category and respective presentation durations.

All statements were presented in white on a black background (beside the fact which was presented in red to highlight it). Premises were presented with the relation “left of; the facts used the relations “left of” and “right of” (at a 50:50 ratio). Thus, the experiment was designed in a way that in half of the revision problems a fact’s LO could be relocated to the leftmost side of the initial arrangement in the other half of the problems to the rightmost side. Locations where the arrangements were presented (a vertically central position on the left or the right side of the monitor) were counterbalanced across the experiment.

Stimuli presentation. Problems were presented using Presentation® software (Version 13.0, www.neurobs.com) in an event-related-design with 12 separate blocks. Each block contained two revision and two maintenance problems in a pseudo-randomized order. The order of problems was randomized across participants and presented with a ±1.5s jitter. The time interval was carefully chosen to ensure that participants had enough

time to integrate premise information into a mental model. Premises were sequentially shown for 5s followed by an arrangement presentation for 3s. The fact was presented for 10s, the decision phase where participants select the correct arrangement taking the fact into account for 7s, hence one trial took 30s. Number of correct decisions and corresponding decision times were recorded.

All problems were projected by a LCD projector onto a screen, with the screen positioned at the head end of the scanner (visual field = 18°). Participants viewed the screen on a mirror mounted on the head coil.

Magnetic resonance imaging. Local variations in blood oxygenation level dependent (BOLD) response were measured, using a 1.5-T whole-body magnetic resonance tomograph (Siemens Symphony) with a standard head coil. Structural image acquisition consisted of 160 T1-weighted sagittal images (MPRage, 1 mm slice thickness). For functional imaging, a total of 505 volumes were recorded, using a T2*-weighted gradient echo-planar imaging sequence (EPI) with 30 transversal slices covering the whole brain (slice thickness = 4mm; descending slice order; voxel size 3.0×3.0×4.0 mm; echo time (TE) = 55 ms; time of repetition (TR) = 3s; flip angle = 90°; field of view = 192 mm × 192 mm; matrix size = 64 × 64). Orientation of axial slices was parallel to the AC-PC line. Data were preprocessed and analyzed using Statistical Parametric Mapping (SPM8, Wellcome Department of Cognitive Neurology, London, UK, 2008) implemented in Matlab R2008a (Mathworks Inc., Sherborn, MA.). Data were preprocessed (realignment and unwarping, slice time correction, coregistration of functional data to each participant's anatomical image, and normalization to the standard space of the Montreal Neurological Institute brain template (MNI-brain). Smoothing was executed with a 7 mm (FWHM) isotropic Gaussian kernel. For each participant, all events were modeled, using a general linear model (GLM) in the first level. The six movement parameters of the rigid body transformation (received from the realignment procedure) were added as covariates in the model. Time series were filtered with a high pass filter of 128 s. T-contrasts were set for each participant (revision – maintenance = corresponding to the fact presentation in this experiment, respectively for both conditions) and afterwards analyzed at the group level.

Exploratory whole brain analyses (*T*-test) were conducted using a corrected (family-wise-error FWE) $p < .05$, $k > 5$ voxels for a comparison. Labeling of the regions was done with MARINA (Walter et al., 2003). Labeling of Brodmann areas (BAs) was done on the basis of Talairach and Tournoux (1988).

Results

Behavioral Data. Participants selected in both, revision and maintenance conditions, over 90% of the correct arrangements (*revision*: $M = 91\%$; $SD = 9.85$; *maintenance*: $M = 93\%$; $SD = 7.97$). Accuracy did not differ significantly between the conditions, *Wilcoxon test* $z = -.95$ $p = .34$; a similar result was achieved by the sample of the pre-study: correct answers in 90% ($SD = 7.60$) of the cases.

The analysis of response times (ANOVA with the factors revision \times maintenance) revealed that participants needed roughly the same time to come up with correct responses in both conditions (*revision*: $M = 2.11$ s; $SD = 0.55$; *maintenance*: $M = 2.21$ s; $SD = 0.85$; $p = .58$).

fMRI Data. An exploratory whole brain conjunction analysis was conducted, comparing the two main factors: revision (preceded by an inconsistency detection) vs. maintenance (preceded by a consistency confirmation) performance. The fMRI results are summarized in table 1.

Table 1
Hemodynamic responses for the whole brain analysis (contrast revision – maintenance).
 (BA = Brodmann labeling; k_E = Clustersize)

| Anatomical Region | Cluster k_E | <i>T</i> | Talairach Coordinates | | |
|---|---------------|----------|-----------------------|-----|----|
| | | | x | y | z |
| Cluster bilateral parietal-postcentral*** | | | | | |
| Inferior parietal, but supramarginal and angular gyri, left (BA39) | 50 | 9.68 | -36 | -43 | 43 |
| | | 8.15 | -51 | -31 | 40 |
| Postcentral gyrus, left (BA1-3) | | 7.32 | -38 | -34 | 40 |
| Supramarginal gyrus, right (BA40) | 39 | 8.62 | 36 | -34 | 40 |
| Inferior parietal, but supramarginal and angular gyri, right (BA39) | | 8.00 | 36 | -40 | 46 |
| Postcentral gyrus, right (BA1-3) | | 7.78 | 42 | -28 | 43 |

| | | | | | |
|--|-----|-------|-----|-----|-----|
| Cluster left parietal*** | | | | | |
| Superior parietal gyrus (BA7) | 79 | 9.55 | -21 | -70 | 43 |
| | | 9.08 | -30 | -49 | 55 |
| | | 8.49 | -27 | -58 | 58 |
| Cluster precentral*** | | | | | |
| Precentral gyrus left (BA4) | 49 | 10.09 | -54 | -1 | 37 |
| Precentral gyrus right (BA4) | 28 | 8.46 | 51 | 5 | 31 |
| Cluster bilateral frontal*** | | | | | |
| Supplementary motor area, left (BA6) | 117 | 8.85 | -3 | -4 | 58 |
| | | 8.81 | -12 | 2 | 67 |
| | | 8.56 | 0 | 14 | 49 |
| Superior frontal gyrus, dorsolateral, right (BA8) | 6 | 8.58 | 21 | 5 | 58 |
| Cluster bilateral Thalamus*** | | | | | |
| Thalamus, left | 138 | 13.35 | -6 | -19 | 7 |
| | | 13.28 | -13 | -22 | 10 |
| Thalamus, right | | 8.50 | 12 | -19 | 7 |
| Cluster bilateral occipital*** | | | | | |
| Calcarine fissure and surrounding cortex, bilateral (BA18) | 63 | 9.05 | 9 | -73 | 16 |
| | | 8.83 | 3 | -82 | 10 |
| Lingual gyrus, left (BA19) | | 7.27 | -9 | -79 | 4 |
| Fusiform gyrus, right (BA19) | 14 | 8.34 | 33 | -61 | -20 |
| Lingual gyrus, right ** (BA19) | 5 | 7.61 | 18 | -58 | 1 |
| Lingual gyrus, left ** (BA19) | 5 | 7.05 | -18 | -67 | 1 |
| Cluster left temporal*** | | | | | |
| Inferior temporal gyrus, (BA20) | 25 | 9.13 | -48 | -55 | -8 |
| Cluster left Putamen*** | | | | | |
| Lenticular nucleus, Putamen | 44 | 9.17 | -18 | 8 | 4 |
| Cluster left Insula*** | | | | | |
| Insula | 12 | 7.62 | -33 | 17 | 7 |

The conjunction analysis for the revision phase (revision – maintenance) revealed activation in a bilateral parietal-postcentral network, including supramarginal and angular gyri, as well as the left superior parietal gyrus. Bilateral fronto-precentral activation leads to a peak in the left supplementary motor area. The bilateral occipital part of the human brain (lingual and fusiform gyri) shows an increase in neuronal activity as well as the left inferior temporal gyrus. Additionally, the thalamus shows bilaterally significant higher neuronal activation, whereby the left part of the putamen and insula are also active, respectively. An overview is shown in figure 2.

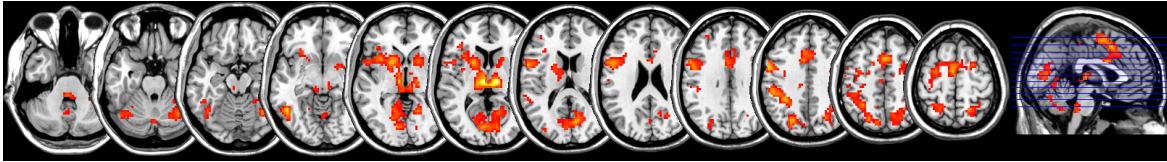


Figure 2. Significant activations for the inconsistency detection and revision phase (whole brain analysis, FEW-corrected, $p = .05$), images are shown in neurological orientation (left hemisphere on the left side). Activated brain regions are: Thalamus, central region (precentral & postcentral gyrus), parietal lobe (inferior & superior parietal gyri), putamen, inferior temporal lobe, occipital lobe (lingual & fusiform gyri), frontal lobe (medial & lateral), and insula.

Discussion

Following behavioral experiments conducted in the field of spatial belief revision and neuro-imaging studies concerning spatial reasoning and error detection, we investigated underlying neuronal correlates of spatial belief revision. Assuming that humans revise spatial beliefs on the basis of mental models, a distinct neuronal activity in visuo-spatial brain regions was expected. As a first step towards investigations of spatial belief revision, the present study focuses mainly on the inconsistency detection and mental model variation process. We decided to modify the method used for behavioral studies as less as possible. Due to this, participants were confronted with an “active” construction phase although the focus of the present study lies in the subsequent inconsistency detection and revision phase. The critical point in time in the experiment is when participants receive the indisputable fact – in the present case either a consistent conclusion, or a contradicting fact. At first glance it does not matter whether this fact is consistent or inconsistent, because for both cases humans need to maintain the initially constructed mental model, to process the new information and to inspect the mental model with the aim to check out concordances or inconsistencies. In cases of inconsistencies a modification of the initially constructed mental model is unavoidable, if consistency is intended. Differences in neuronal activities between both conditions might reflect the cognitive demand and neuronal correlates for inconsistency detection processes, as well as the revision process itself. Although in the present study inconsistency detection and revision were not explicitly disentangled, results underpin the assumption that human reasoning is based on mental models, showing a clear increase of neuronal activity in a parietal-

frontocentral-occipital-temporal network. The results support the assumption about an association between activations in parietal regions and spatial reasoning, on the basis of mental models (for overviews see Knauff, 2009; 2013; Sack, 2009). The following is intended to discuss some possible implications.

Inconsistency detection

We start the inconsistency detection phase with activations in the dorsolateral superior frontal gyrus and the inferior parietal lobe (supramarginal and angular gyri) following the “mental model processing” phase suggested by Knauff (2009). Both regions are correlated with the executive and intentional control of human behavior, working memory capabilities and are typical for deriving conclusions in deductive reasoning (Kübler, Dixon, & Garavan, 2006; Reverberi et al., 2007) – all capabilities of crucial importance to pave the way for an inconsistency detection. Additionally, the superior frontal gyrus is associated with higher cognitive functions especially with spatial content. It seems to be a crucial component in the working memory network and spatially oriented processing. Monitoring and manipulation of mentally represented information is also attributed to the superior frontal gyrus (Du Boisgueheneuc et al., 2006). For this reason, the superior frontal gyrus might be a central component in the inconsistency detection phase assuming that the inconsistency detection requires an inspection of an initially constructed mental model in order to compare premise information represented by a mental model, and the indisputable fact.

In addition, the left insula is involved in rehearsal processes of verbal material and speech production (Fiez et al., 1996; Ackermann & Riecker, 2004; Bamiou, Musiek, & Luxon, 2003), but for the present study more relevant, the insula is also activated during error processing (Menon, Adleman, White, Glover, & Reiss, 2001), high-level cognitive control and attentional processes. It seems to be an interface between external detected salient information and self-regulative processes, in order to guide behavior. For this reason it is reasonable to assume that the insula is mainly responsible for forwarding essential information to downstream revision processes, because the insula is involved in

attentional switching processes and working memory capacities management, as well as in preparing a rapid access to the motor system (Menon & Uddin, 2010).

Spatial belief revision

Activations in a parieto-fronto-central network (including the supramarginal gyrus, inferior and superior parietal lobules, and sensory cortex of the parietal lobes, the supplementary motor area, and the premotor regions of the frontal lobes) are associated with action-related language processing and grounded cognition (Hauk Johnsrude, & Pulvermüller, 2004; Pulvermüller, 2005; Tettamanti et al., 2005; Boulenger, Hauk, & Pulvermüller, 2009; Raposo, Moss, Stamatakis, & Tyler, 2009; Esopenko et al., 2012). The angular gyrus, as a part of the inferior parietal lobe is functionally connected to occipito-temporal brain regions, as well as language areas in the superior temporal and inferior temporal cortex (Pugh et al., 2000).

The temporo-occipital network is generally associated with language processing (e.g. single word processing; Horwitz, Rumsey, & Donohue, 1998), but Knauff (2009) suggests the temporo-occipital network to be involved in premise processing in a way that a visual mental image is formed on the basis of given information, together with general knowledge about the specific situation and the entities that are mentally maintained in working memory. In this context it is essential, that according to the grounded cognition approach cognitive representations and modal systems are closely related. Mental simulations are proposed to establish the link between cognitive representations, perception, and action (Barsalou, 2008). Furthermore, language comprehension seems to be coupled with spatial representations (Rinck & Bower, 2004), and additionally, a close connection between conceptual representations and a simulation-based language understanding is suggested (Bergen & Chan, 2005). The reading of a word that represents a specific action for instance, appears to be sufficient to elicit activation of the motoric system (Pulvermüller, 2005; Aziz-Zadeh, Koski, Zaidel, Mazziotta, & Iacoboni, 2006; Barsalou, 2008; Barsalou, 2010).

For spatial belief revision these assumptions and findings could imply that processing of a verbal presented inconsistent fact that implies a relocation of a certain object in order to regain consistency might result in a simulation of this relocation. One suggestion for spatial belief revision is that objects are mentally represented by tokens in a mental model and that the revision process relies on a local transformation in which a token is moved to a new position in the model (e.g. Knauff et al., 2013). This assumption is compatible with experimental findings from behavioral studies concerning spatial belief revision, showing that humans mentally relocate preferably small objects compared to large objects and that the inherent movability of an object modulates revision durations (Nejasmic et al., 2013; under review).

Even the – in behavioral experiments rather curious – finding that weight does not affect the way reasoners revise their spatial beliefs can be better understood by looking at the neuronal correlate (Nejasmic et al., under review). The fusiform gyrus as well as the lingual gyrus are supposed to be correlates of attention control, reading capabilities and visual-spatial processing, assuming that the fusiform gyrus is engaged in processing of local stimuli features, whereby the lingual gyrus is related to global shape processing (Bogouslavsky, Miklossy, Deruaz, Regli, & Assal, 1986; Mechelli, Humphreys, Mayall, Olson, & Price, 2000). Additionally, the right fusiform gyrus, also known as the face-area (Kanwisher, 2000) is suggested to be responsible for a more general and complex object recognition (Chao, Martin, & Haxby, 1999). Activations in these regions support the assumption that obviously visible object properties like size and properties better visible than weight, such as e.g. movability influence spatial belief revision, whereby weight has to be derived using an “indirect route”, e.g. by estimating the weight of an object by its size (Flanagan & Beltzner, 2000; Zhu & Bingham, 2010).

Due to the fact that objects used in the present study did not differ essential regarding their properties, we assume, that the temporo-occipital network might has been used to select the respective object of interest for a relocation by evaluating the asymmetry between the two objects (LO and RO) of an inconsistent fact, and that the relocation of the facts LO within the mental model is simulated (Bucher, et al., 2011; Krumnack, et al.,

2011; Bucher & Nejasmic, 2012; Bucher, et al., 2013; Knauff, et al., 2013; Mikheeva, et al., 2013; Bucher & Thorn, 2014; Nejasmic, et al., 2014; Nejasmic, et al., 2013; Nejasmic, et al., under review).

Additionally, activations in the putamen and the superior parietal lobe support the assumption of a mental simulation of tokens within a mental model. Whereby the superior parietal lobe is responsible for the supervision of movements and top-down guidance of attentional control (Hopfinger et al., 2000), is the putamen closely related to motor functions. Furthermore, the putamen is functionally connected with the motor cortex and the supplementary motor area, as well as the thalamus (Crosson et al., 2003; Robles, Gatignol, Capelle, Mitchell, & Duffau, 2005).

Findings suggest that information from somatosensory association, motor, and prefrontal areas are coupled by the putamen, which transmits processed information via the thalamus back to different cortices (Macchi & Bentivoglio, 1994; Tisch, Silberstein, Limousin-Dowsey, & Jahanshani, 2004). The thalamus appears to play a major role in selective engagement processes, language and verbal memory (e.g. Bhatnagar & Mandybur, 2005). In the literature it is described as a central hub between sub cortical and cortical areas. New information is filtered in the thalamus and just the important one is forwarded to respective cortical areas (Alexander, de Long, & Strick, 1986), an aspect of particular relevance for spatial belief revision. Additionally the thalamus is closely related to conceptual thinking capabilities, cognitive flexibility, behavior inhibition, and detection of novelties (Aggleton & Brown, 1999; van der Werf, Witter, Uylings, & Jolles, 2000; van der Werf, Jolles, Witter, & Uylings, 2003; Zoppelt, Koch, Schwarz, & Daum, 2003).

Based on this, the thalamus could play a crucial role for spatial belief revision by filtering essential information from an inconsistent fact and taking motor planning information from the putamen and inferior parietal lobe into account. Action related information could be processed in the thalamus and forwarded to motor related areas (pre- and postcentral regions, as well as supplementary motor area).

To sum up, most of the regions engaged in the present study are related to motor executions, spatial orientation, and language processing (Tanji, 1994; Picard & Strick,

1996, Rizzolatti, Fadiga, Gallese, & Fogassi, 1996) and we conclude that verbally presented spatial information is incorporated in mental models and that revision processes are performed by mental relocations of tokens within these models. Results of the present fMRI study underpin the assumptions that the revision processes is indeed a local transformation of mentally represented objects that are most likely processed and integrated by taking visuo-spatial brain regions into account and that humans simulate the “revision movement”. Spatial belief revision leads to neuronal activation in the dorsolateral frontal gyrus, pre- and postcentral gyri, with the supplementary motor area, superior and inferior parietal lobes (supramarginal and angular gyri), the lingual, fusiform and inferior temporal gyri, putamen, insula and thalamus.

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Part 5

Chapter 8

Plausibility and visualizability in relational belief revision⁸

⁸ This work was published in a slightly different form in: Bucher, L., Nejasmic, J., Bertleff, S., & Knauff, M. (2013). Plausibility and visualizability in relational belief revision. In M. Knauff, M. Pauen, N. Sebanz, & I. Wachsmuth (Eds.), *Proceedings of the 35th Annual Conference of the Cognitive Science Society* (pp. 1946-1951). Austin, TX: Cognitive Science Society.

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 counterfactuals. 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.

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 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 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; DeNeys, 2006; Evans, 2008; 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 visualizability 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 inverse 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 ($ps > .05$).

Plausibility: ANOVAs were calculated, with the factors Plausibility (plausible, implausible) \times 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: $F(1,19) = 71.91; p < .001; \eta^2_{part} = .79$; duration: $F(1,19) = 6.53; p = .019; \eta^2_{part} = .26$; all other $ps > .20$). 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; $SD = 1.74$; $t(19) = -2.35; p = .03$.

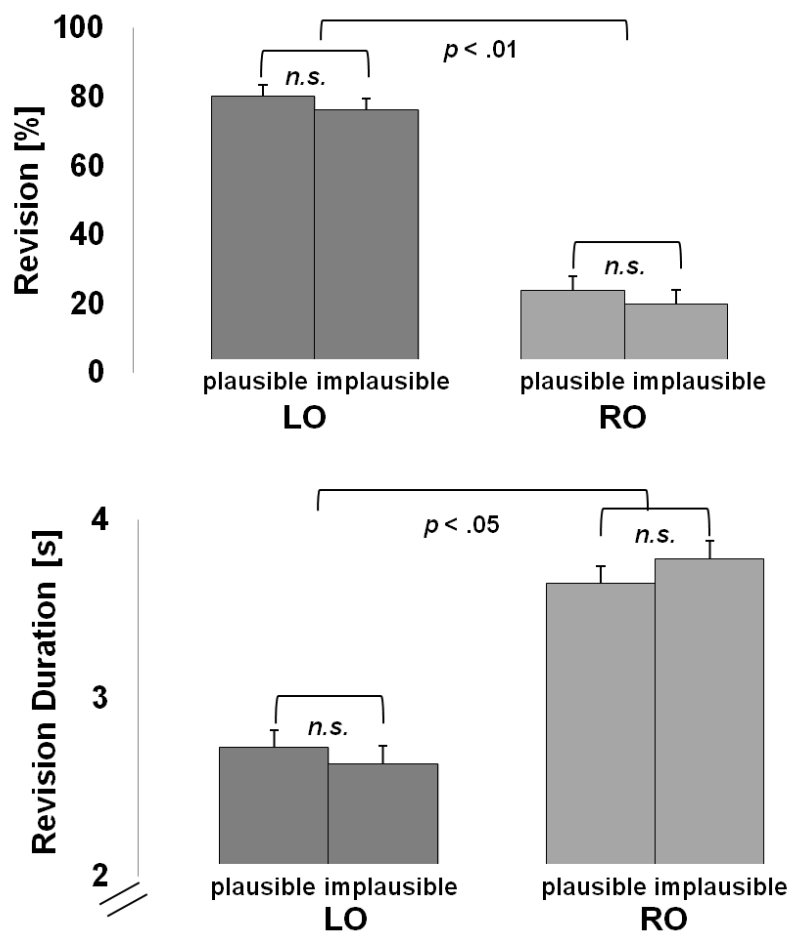


Figure 1. Revisions [%] and revision durations [s; error bars indicate standard errors] of “located” (LO) and “reference” objects (RO) showed an LO-effect. The preference was not modulated by plausibility.

Figure 1 provides a graphical 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, $F(2,18) = 4.80$; $p = .014$; $\eta^2_{part} = 2.02$. 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 ($p > .35$).

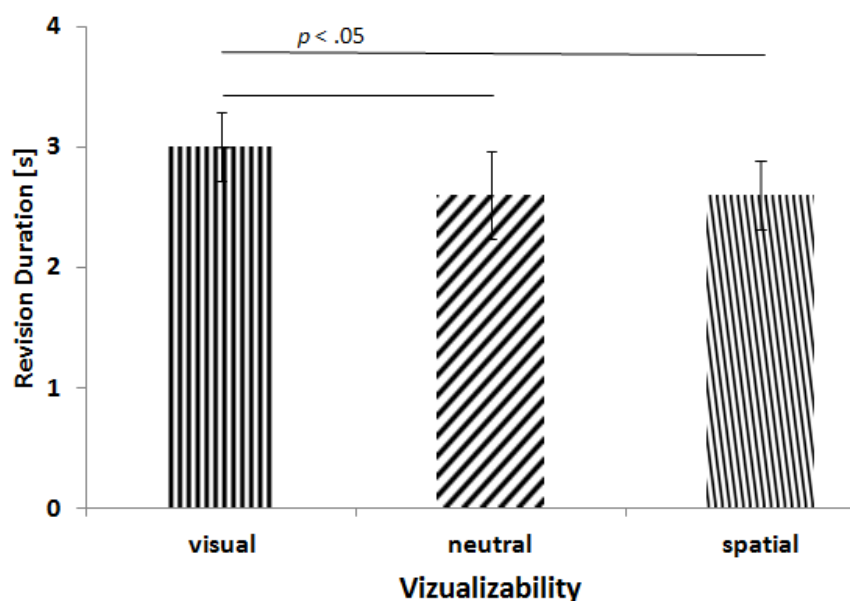


Figure 2. Mean revision durations of different relation types indicate a visual impedance effect. Error bars indicate standard errors.

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; DeNeys, 2006; Evans, 2008; 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 visualizability 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; Schaeken, Johnson-Laird, & 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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Chapter 9

Spatial reasoning in nativ speakers of russian and german⁹

⁹ This work was published in a slightly different form in: Mikheeva, M., Bucher, L., Nejasmic, J., & Knauff, M. (2013). Spatial reasoning in native speakers of Russian and German. In M. Knauff, M. Pauen, N. Sebanz, & I. Wachsmuth (Eds.), *Proceedings of the 35th Annual Conference of the Cognitive Science Society* (pp. 3038-3043). Austin, TX: Cognitive Science Society.

Abstract

The relationship between reasoning and language has been frequently studied. Here we explore principles of spatial reasoning in Germans and Russians. We compared the performance of Russians in three different settings to the performance of Germans. The task was to construct layouts of wooden blocks according to verbal instructions, describing the relations of these blocks. Subsequently pieces of new information, introduced as incontrovertible facts and partly contradicting the initial descriptions, were given. Participants re-arranged the blocks to take into account the new facts. Recent research conducted with Germans has shown that – although alternatives are logical equivalent - there are preferences for certain solutions. The question was whether Russians show the same or different preferences. Our results suggest that construction and revision of spatial models follow similar principles. However, we observed differences between the groups regarding the flexibility to apply a principle based on the order of words in a sentence.

Introduction

Misunderstandings happen so often between people from different countries, triggering the important question: how is language connected to our mental representation of the world? What role does it play in reasoning? Answers suggested to that question are provided by an important theory in that area: the Sapir-Whorf hypothesis affirms that language influences thought (Zvegintsev, 1960; Levinson, Kita, Haun, & Rasch, 2002; Levinson & Meira, 2003). On the other hand, there is the view that the mind is organized in a modular way with separate modules dedicated to certain abilities (e.g. Tsimmerling, 2000; Nowak, Komarova, & Niyogi, 2001; Kulikov, 2012). A further important question, to some extent related to language, is: how do mental representations differ across different cultures? What role do cultural backgrounds play in reasoning? While some studies suggest cultural dissimilarities (e.g. Oyserman & Lee, 2008), other studies show that there are common cognitive principles used by reasoners of different cultures. Cross-cultural

similarities have, for instance, been shown in topological reasoning (Knauff & Ragni, 2011; Knauff, 2013). The present study is concerned with spatial relational reasoning and the influence of language and culture. We briefly analyze relevant work on linguistic influence on thinking, comparative topology of German and Russian, and spatial relational reasoning. We then present an experiment, designed to investigate the construction and revision of spatial models.

Construction and Revision of Spatial Mental Models

Imagine you need to find the house № 28 in a street, unfamiliar to you. You have received the following description of the precise location by friend A, informing you that:

- (1) “There is a hotel to the right of a café.”, and
- (2) “The house № 28 is to the left of the café.”

The description allows for one (determinate) model to construct. In order to construct the model, spatial information is inserted successively. Based on the information given by statement (1), the model

(3) “Café – Hotel” is initiated and extended by (2) “House № 28”, resulting into the model:

- (4) House № 28 – Café – Hotel

A lot of studies have explored factors that influence reasoners when they construct models, among them the order of objects as inserted into the model, and other order effects (e.g. Ehrlich & Johnson-Laird, 1982; Payne, 1993; Payne & Baguley, 2006; Bucher, Krumnack, Nejasmic, & Knauff, 2011; Krumnack, Bucher, Nejasmic, & Knauff, 2011; Nejasmic, Krumnack, Bucher, & Knauff, 2011).

Imagine you find out a little later that the information uttered by friend A is unreliable. Friend B – who lives in the street in question – informs you that as a fact:

(5) “The house № 28 is to the right of the hotel.”

The more reliable and incontrovertible information partially contradicts friend A’s description needs to be taken into account. The following alternatives are possible:

(6) Café - Hotel - House № 28

(7) Hotel – House № 28 – Café

Both variations of the initial model are logically equivalent. Nevertheless, when confronted with ambiguous relational information, human reasoners frequently prefer one alternative over the other (Jahn, Knauff, & Johnson-Laird, 2007; Krumnack, Bucher, Nejasmic, & Knauff, 2010; Bucher et al., 2011; Krumnack, Bucher, Nejasmic, Nebel, & Knauff, 2011; Bucher & Nejasmic, 2012; Knauff, Bucher, Krumnack, & Nejasmic, 2013).

Preferred model revision

The process of model revision with verbal descriptions, using binary relations $r(X,Y)$ as facts has been shown to rely on the following principle: the functional distinction of X as the “to-be- located object” (LO) in contrast to Y as the “reference object” (RO) specifies the location of the LO relative to the known location of the RO (e.g. Huttenlocher & Strauss, 1968; Miller & Johnson-Laird, 1976; Talmy, 1983; Landau & Jackendoff, 1993). For the revision of horizontal linear arrangements, the following finding concerning reasoners’ preferences is characteristic

| | |
|---------------------|---|
| Initial arrangement | A B C |
| Counterfact | C is left of A, with C as the relation’s LO |
| Preferred revision: | C A B |

Note that the logical equivalent (non-preferred) alternative for revising the initial model by relocating the counterfact’s RO (here: A) would results in the revised model: B C A. We refer to the preferred principle as the LO-principle (compared to the RO-principle).

Linguistic Influence on Thought and Comparative Typology of German and Russian Languages

The Sapir–Whorf hypothesis postulates that language determines thought or at least that linguistic categories influence thought and certain kinds of non-linguistic behavior (Zvegintsev, 1960). Li and Gleitman (2002) investigated influences of individual languages (e.g. English and Dutch) on spatial reasoning. Chatterjee (2011) studied language as a form of mental representation of space. With the current study, we investigate influences of different languages (Russian vs. German) on spatial mental representations. Moreover, to dissociate between influences that result from linguistic aspects on the one and cultural aspects on the other hand, the study took place in two cultural settings (in Germany and in Russia).

First, we briefly explain the structures of both languages in terms of comparative typology. Both languages are from the Indo–European family. German belongs to the West Germanic family, Russian is a Slavic language. They are inflexional languages (from Lat. *Flectivus* «flexible»). The term refers to a language, where word-building with inflexions dominates. Inflexions are morphemes which can have much significance; e.g. the article „die“ (as in “die Katze”, “the cat”) in German, indicates the gender (feminine), the case (nominative), and the number (singular). Russian is even more inflexional compared to German. Inflexional languages can be synthetic or analytic. The German language is between the synthetic and analytic languages, it has some characteristics of both language types. In a synthetic language, a word contains all the grammar, e.g., by inflexional endings, prefixes, suffixes. An analytic language is a language which reproduces grammatical relationships syntactically. Accordingly, it uses only unbound morphemes, and only separate words like articles etc. (Anokhina & Kostrova, 2006). For instance: “хорошая новость” and “eine gute Neuigkeit” (“good news”) – in Russian, the ending „ая“, and in German the (additionally needed) article „eine“ indicates: feminine, nominative, singular. There are some more differences between German and Russian which we do not want to explain here in detail. What is relevant for the current study is the flexibility in word order in the two languages. In German, the possibility of ordering

words within a sentence in a certain way is much more limited compared to Russian. Of course, the “freedom” of word order in Russian is not unlimited and also regulated by semantic and stylistic factors (as in German) (Anokhina & Kostrova, 2006). An example is given in table 1.

Table 1.
Word order in German and Russians languages

| Russian | German | Exact meaning |
|--------------|----------------------------------|---|
| Я люблю тебя | Ich liebe Dich | I love you |
| Тебя я люблю | <i>Word order not possible</i> | I love you, exactly you, not another person |
| Я тебя люблю | <i>Word order not possible</i> | I love you, exactly you, not another person |
| Люблю я тебя | <i>Word order not possible*</i> | I love you (with an even stronger significance in the sense that I can do nothing about it) |
| Люблю тебя я | <i>Word order not possible**</i> | You are loved by me, not someone else |
| Тебя люблю я | Dich liebe ich | I love you, exactly you, not another person |

*the word order would be possible in a German question (“Liebe ich Dich?”); **the word order would be possible in a German passive sentence (“Du wirst von mir geliebt.”)

Analogously, the Russian spatial language is also more flexible than the German language. For example, dynamic local relations in German indicate source locations (“where from?”) and directions of motion (“where to?”), while in Russian such relations have a triple function, they indicate: location (“where”), source location, and direction (Khoruzhaya, 2007).

To summarize, there are major differences between German and Russian. Previous research on spatial relational reasoning suggests that reasoners have strong preferences which are often based on linguistic cues that are connected to the sentence structure. The main finding in a range of experiments on the variation of spatial models (Bucher et al., 2011; Krumnack et al., 2011; Bucher & Nejasmic, 2012; Knauff et al., 2013) is that the variation is preferably done by the relocation of objects that are perceived as more flexible compared to other objects. These objects are usually the so called to-be-located objects (LO) of a relational statement as compared to reference objects (RO) which are perceived as more stationary. We refer to this preference as the LO-principle.

The question is whether cognitive principles such as the LO-principle are used independently from linguistic or cultural aspects. Concerning the language aspect, it would be plausible if Russians, i.e. native speakers of a language that is by nature very flexible concerning the word order and sentence structure are accordingly more flexible in the application of such cognitive principles. In this specific case they might use the RO-principle more frequently as an alternative solution in the reasoning task. Culture is another important aspect to look at when we look at similarities of cognitive principles. There are many definitions of culture. Oyserman and Lee (2008, p. 311) say that “culture matters to the extent that individuals living in different societies are likely to have differing experiences”. Criado (2009, p. 295) explains that culture is “a set of shared values, beliefs, expectations, customs, jargon, and rituals”. What seems to be indisputable is that a cultural environment can have an impact on the way an individual thinks. In order to explore both, language and culture influence, we conducted the same experiment with native speakers of German and of Russian as participants. Three different samples of Russian participants were tested in two different cultural environments:

1. The first sample was tested in German, in Germany
2. The second sample was tested in Russian in Germany
3. The third sample was tested in Russian in Russia

The purpose was to control for both, the language and the cultural setting.

Experiment: Construction and Revision of Block Arrangements

Method

The first part of the experiment can be referred to as “construction phase”. The task was to physically construct layouts of wooden blocks according to a verbal instruction, describing the relations of these blocks. The second part can be titled “revision phase”. Once a layout was constructed, a piece of new information, introduced as an

incontrovertible fact contradicted a part of the initial description. The task was to rearrange the blocks such that it cohered with the “fact”.

Participants. Altogether, we tested 76 volunteers who performed in the task either in German or in Russian in Germany or in Russia. All participants gave informed consent to participation. Participants were tested individually. Each participant was tested only once. Language abilities were assessed by self-report. Russian participants tested in Germany rated their German language abilities as “very good”, and reported to be capable of writing and speaking fluently. They were fluent in Russian as their mother tongue and in German as a second language, and have been living and were educated in Germany for a considerable time. Russian participants tested in Russia reported to be not familiar with the German language while German participants reported to be not familiar with the Russian language.

The sample of Germans tested in German in Germany consisted of 11 (5 male; age: $M = 24.91$; $SD = 2.95$) native speakers of German, all students from the University of Giessen. None of them has ever studied Russian.

The sample of Russians tested in German in Germany consisted of 19 (3 male; age: $M = 24.05$; $SD = 4.18$) native speakers of Russian.

The sample of Russians tested in Russian in Germany consisted of 20 (3 male; age: $M = 25.45$; $SD = 5.26$) native speakers of Russian.

The sample of Russians tested in Russian in Russia consisted of 26 (1 male; age: $M = 20.35$; $SD = 0.63$) native speakers of Russian. They were all students from the Federal University of Kazan (among them 19 students of psychology). None of them has ever studied German or visited Germany.

Materials, Procedure, and Design. 32 items were presented, each consisting of two premises and an inconsistent fact. The task was presented on a 19``-computer screen, using Microsoft PowerPoint (Version 2007) running in the windows environment XP on a standard personal computer. PowerPoint slides were presented by the experimenter in a sequentially and individually adapted manner according to participants’ performance. In

all items, the two premises and the contradictory fact (presented in red) had the surface structure as follows: first object - relation (either “left of” or “right of”) – second object.

Example: “Yellow left of red”

Participants were provided with wooden square blocks (size: 2.5 x 2.5 x 2.5 cm), red, green, yellow, and blue colored on a plate in front of them and instructed to construct and subsequently revise their block layouts.

The construction phase: participants were instructed to pick up the colored blocks, one at a time using one hand, and arrange them according to the information provided by the premises into a linear one-dimensional order. The premises informed about the determinate order of the blocks with the blocks represented by the respective colors (red, green, yellow, and blue).

Example:

1st premise: “Blue right of red”

2nd premise: “Green right of blue”

Spatial arrangement: red – blue – green

The location of the third object was counter-balanced across all problems. In a recent experiment, very similar to the one reported here, and presented in German to German participants, word order has been shown to be crucial for the physical construction of spatial models (Bucher et al., 2011, Experiment 2). Here, accordingly, based on the description of the 1st premise, two possible construction orders were possible:

1. Starting on the left side and continue to the right, e.g. (consider the 1st premise from the above example) putting down the red block first and placing the blue block to the red one’s right side.

2. Starting on the right side and continue to the left, e.g. putting down the blue block first and placing the red block to the blue one's left side

The resulting orders are describable as 1 – 2 – 3 and 2 – 1 – 3, with the numbers indicating the order by which objects had been put down; e.g. red first – blue second – green third (order 1 – 2 – 3) and red second – blue first – green third (order 2 – 1 – 3). The question was whether there would be order effects when constructing the arrangements in the Russian samples similar to those found in Germans.

The revision phase: subsequently after participants had constructed the order of the three colored blocks, they were asked to revise their order according to the inconsistent fact.

Example-fact: “Green left of red”

Participants were free with the revision of their initially constructed arrangements. After each trial, the wooden blocks were put back onto the plate by the experimenter. Four practice trials (neither recorded nor analyzed) preceded the experimental trials. Performance was recorded on a video tape by the experimenter and analyzed after the experimental session (Bucher et al., 2011). In previous experiments, using a very similar experimental set-up, presented in German to German participants, the finding was that of a clear preference (e.g. 89.52 %, $SD = 11.30$; see Bucher et al., 2011, experiment 2) of LO relocations as compared to RO relocations. The question was whether participants of the Russian samples would apply the LO-principle similarly to the German participants.

Results and discussion

Construction. Mean percentage rate of correctly constructed orders was 97% ($SD=4.46$). There was no difference in number of mistakes in construction between the samples ($p > 0.30$). We analyzed the order of objects put down during the construction in every sample, running Wilcoxon's tests for each sample, separately (Siegal & Castellan, 1988). In the German sample the 1-2-3-order was used more frequently compared to the 2-

1-3-order ($z = -2.01$; $p < .05$). The same applies to the remaining samples: Russians tested in German in Germany ($z = -3.93$; $p < .01$), Russians tested in Russian in Germany ($z = -3.97$; $p < .01$), and Russians tested in Russian in Russia ($z = -4.49$; $p < .01$). Our results provide evidence that the same principle (putting down blocks in word order 1-2-3 rather than in the order 2-1-3) was applied similarly by participants of all four samples. Thus, we can conclude that the cognitive principle is not affected by linguistic aspects. Russians tested in Germany as well as Russians tested in Russia used the same principle, suggesting cross-cultural similarities. We continued our analysis by comparing the magnitude of the preference applied by Germans and Russians in the different settings. The Kruskal-Wallis test revealed a difference between the samples ($p < .05$). Pair wise comparisons, using Wilcoxon's tests revealed that the group of Germans differed from all Russian samples (all $ps > .05$). Despite the overall similarities found across all samples, we found that Russians were more strictly in the application of this principle. The Germans performed more flexible in the task, using the alternative word order (2-1-3) more frequently. Figure 1 depicts the result graphically. We continue to discuss this difference in the General Discussion of this paper.

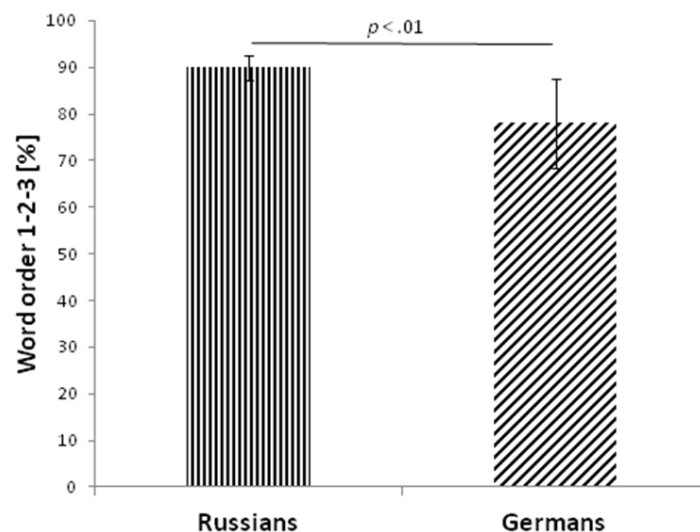


Figure 1. The figure depicts the difference between Germans and Russians during the construction of block arrangements. The word order effect was more pronounced in Russians than in Germans. Error bars indicate standard errors.

Revision. Mean percentage rate of correctly revised models was 99.14% ($SD = 1.74$). There were no differences in the amount of mistakes between the samples ($p > 0.40$). Erroneous problems were excluded from further analyses. We ran Wilcoxon's tests for each sample, separately. That was to analyze which principle the revision followed. The tests indicated that in the German sample LOs were relocated more frequently than ROs ($z = -2.95$; $p < .01$). The same principle was applied by reasoners in the other samples: Russians tested in German in Germany ($z = -3.83$; $p < .01$), Russians tested in Russian in Germany ($z = -3.96$; $p < .01$), and Russians tested in Russian in Russia ($z = -4.56$; $p < .01$). Again, our results suggest similarities across both language groups. There was a clear preference for LO relocations across all samples (figure 2 depicts the results graphically). The principle was equally used by Russian native speakers, who were tested in Russian and in German. This suggests that linguistic aspects were not modulating the effect. Russians tested in Germany as well as

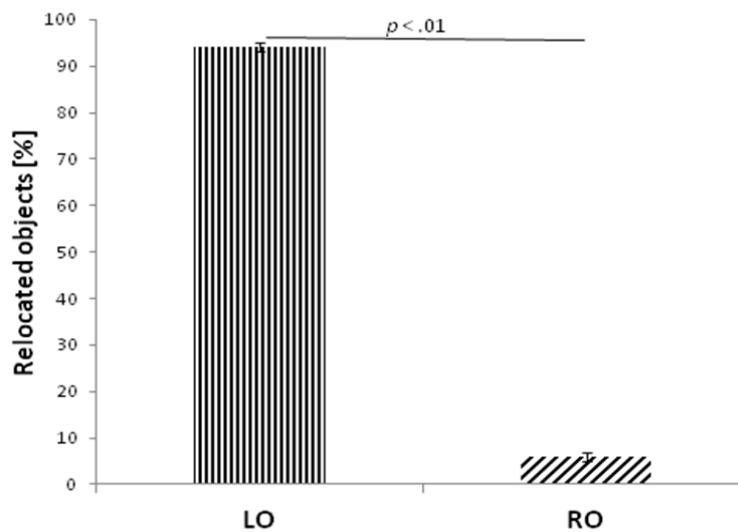


Figure 2. For revision, the LO principle (relocation of the to-be-located object, LO as opposed to the reference object, RO) was preferably applied by participants of all samples. Error bars indicate standard errors.

Russians tested in Russia used the same principle, suggesting similarity across the cultures. We continued our analysis by comparing the magnitude of the preference applied

by Germans and Russians in the different settings. The Kruskal-Wallis test revealed that there are no differences between the samples ($p > .30$). Unlike the word order effect, the LO effect was equally strong across all groups. This finding further corroborates the assumption of a cross-cultural and cross-linguistic cognitive principle.

General Discussion

The present study investigates aspects of spatial relational reasoning in reasoners from Germany and Russia. We explored principles applied for the construction and the revision of spatial models in four types of samples. A sample of German native speakers who were tested in German in Germany, a sample of Russian native speakers, tested under the same conditions, a sample of Russian native speakers tested in their mother tongue but in the German cultural environment, and a sample of native speakers of Russian who were naive to the German language, tested in their native Russian cultural environment.

The study was motivated by recent findings that principles applied by German reasoners in spatial relational reasoning tasks were based on linguistic cues. One study (Bucher et al., 2011) suggests that during the physical construction of spatial (block) arrangements, the word order plays a role in guiding the construction process while for the revision of these models the asymmetry of LOs and ROs of relational statements provide the crucial cues for reasoners (Bucher & Nejasmic, 2012; Knauff et al., 2013). Here as a novelty, a similar task was presented to native speakers of Russian. We were concerned with the dissociation of linguistic and cultural aspects. In order to dissociate these aspects to a certain degree, we splitted the Russian group into three sub-samples, allowing a rough distinction of cultural from linguistic influences. The results indicate cross-cultural similarities for both cognitive principles applied during construction and revision of spatial models. Across all samples (German and Russians), the construction followed the word-order-principle. This effect has been previously shown in Germans (Bucher et al., 2011) and could be repetitively shown here. The revision was found to be guided by the LO-principle. This principle had been repeatedly shown in German reasoners and here – for

the first time – in Russians. The effect was comparable in magnitude across all samples. We conclude that both principles reflect similar mechanisms.

However, Germans used the alternative principle (starting construction with the second object) more often compared to the Russian samples and performed thus construction processes more flexible. Please, note that with the current experiment, it is not distinguishable whether reasoners used the first object mentioned in the premise or the LO as a starting point for their construction, because the first object in a statement was identical with the LO. However, Bucher et al. (2011) argue that different cognitive principles are applied during construction (first vs. second object as starting object) and revision (relocation of LO vs. RO), respectively. The authors also provide empirical evidence for their view. The results of the current study show that German native speakers are more flexible when applying the word order principle, compared to Russians, while the LO-principle is applied equally robustly by both groups. This can be taken as corroborating evidence that the cognitive mechanisms underlying construction and revision are distinguishable, however comparable for Germans and Russians.

Nevertheless, we found differences in the manifestations of the word-order effect between the groups. The effect was stronger in Russians compared to Germans. This indicates that Russians used the alternative word order less frequently than Germans did when they constructed their models. When we bear in mind that the Russian language allows for many variations of word orders in a sentence, the result might look counterintuitive, at the first glance. However, we must note that speakers of Russian already make many decisions when they construct a sentence. Maybe, it is the compensation for this “liberty” in the canonical word order of the Russian language which we find reflected by the high adherence to the word order principle. Also important in the present context is that although we might have found cross-cultural similarities between Germans and Russians, as well as cross-linguistic principles that were applied during the construction phase, there is an alternative interpretation of the results. While (as in previous experiments) German reasoners might have based the construction preferably on the word order, it is possible that Russian reasoners applied the LO principle, i.e. put the

LO as first object on the table. With the present study we cannot rule out this alternative interpretation but we are currently running experiments designed to look at this problem.

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Chapter 10

Belief Revision and Way-finding¹⁰

¹⁰ This work was published in a slightly different form in: Bucher, L., Röser, F., Nejasnic, J., & Hamburger, K. (2014). Belief Revision and Way-finding. *Cognitive Processing*, 15(1), 99-106.

Abstract

Belief revision is required when veridical information surfaces that contradicts what was previously thought to be the case. In way-finding, belief revision frequently occurs, for example, when the travelled route has led one astray, instead of to one's chosen destination. In past cognitive research, the topics of belief revision and way-finding have been treated in isolation. Here, we introduce an approach for linking the two fields, and assess belief revision as it occurs in the process of way-finding. We report the results of two experiments which put participants in (virtual) situations where elements of a previously learned route description do not match the actual environment (thereby requiring the revision of a previously held belief). Experiment 1 puts participants in a highly artificial virtual environment where the landmarks to be used in navigation have a low degree of semantic salience (houses of various color). Experiment 2 puts subjects in a photorealistic environment where the objects to be used in navigation are well known landmarks (such as the Eiffel Tower), and thus have a high degree of semantic salience. In both experiments, participants are confronted with T-junctions, where a landmark which was expected to indicate the correct route, is discovered to be in an unexpected location. The results of the experiments show that a participant's choice of route, in such cases, is affected by differences in the structure of the relevant initial instruction. More precisely, the route chosen by participants is affected by whether the relevant landmark was described as being on the same side of the path as they were instructed to turn (congruent case) or as located on the opposite side of the path as they were instructed to turn (incongruent case).

Introduction

Psychological research on belief revision is concerned with how individuals change their beliefs when they are confronted with evidence that contradicts those beliefs. In the past, belief revision has typically been investigated by observing the behavior of subjects in the face of abstract conditional and relational reasoning problems (Revlis, Lipkin, & Hayes, 1971; Elio & Pelletier, 1997; Dieussaert, Schaeken, De Neys, & d'Ydewalle, 2000;

Giroto, Johnson-Laird, Legrenzi, & Sonino, 2000; Revlin, Cate, & Rouss, 2001; Bucher, Krumnack, Nejasmic, & Knauff, 2011; Krumnack, Bucher, Nejasmic, & Knauff, 2011a; Krumnack, Bucher, Nejasmic, Nebel, & Knauff, 2011b; Bucher & Nejasmic, 2012; Wolf, Rieger, & Knauff, 2012; Knauff, Bucher, Krumnack, & Nejasmic, 2013). In the present article, we present a study of belief revision as it occurs in the process of way-finding, and, in particular, within a type of situation that agents face in the course of everyday life.

To begin, we note that way-finding behavior is typically guided by beliefs about how one might get from a starting point to a certain destination. In turn, belief revision occurs in the course of way-finding when a plan to travel upon a preselected route is disrupted, because an assumption (or belief) essential to one's plan to take the route is discovered to be incorrect. In the experiments reported here, participants faced a situation where the goal of navigating by a given landmark is disrupted, when previously given information about the position of the landmark is observed to differ from its actual location.

Way-finding and belief revision in isolation and linked together

Past research has shed much light on the strategies that individuals apply in successful way-finding, and have focused mainly on the multimodal integration of verbal, acoustic, tactile, and even magnetic pieces of information, and on the format of route descriptions (skeletal vs. fully fleshed out, etc.) (e.g., Golledge, 1999; Allen, 2004; Shah & Miyake, 2005; Downs & Stea, 2006; for current research see, e.g., Hamburger & Röser, 2011; Röser, Hamburger, & Knauff, 2011; Röser, Hamburger, Krumnack, & Knauff, 2012). Major effort has also been dedicated to uncovering the nature of "good" landmarks. A prominent model which describes the dimensions along which the "quality" of landmarks can be assessed was proposed by Sorrows and Hirtle (1999). Sorrows and Hirtle suggest that different kinds of saliency, including semantic saliency, play a major role in determining a landmark's "usability" as a means to successful wayfinding.

In cases where an agent is confronted with information that contradicts her previously held beliefs, there are usually multiple ways of revising her beliefs in order to achieve consistency. Studies of this revision process using abstract reasoning problems have shown that individuals hold strong preferences for certain alternatives, even when the alternative solutions are equally acceptable from the standpoint of logic. For example, within deductive reasoning problems, subjects show a preference for abandoning prior beliefs in conditional statements (e.g., if P, then Q) versus non-conditional statements (e.g., P), when presented with a fact (e.g., not Q) that is inconsistent with the two statements, and a similar preference for abandoning beliefs in statements that express generalizations in comparison to those that do not express generalizations (Revlis et al., 1971; Elio & Pelletier, 1997; Dieussaert et al., 2000; Girotto et al., 2000; Revlin et al., 2001). Other studies have shown that, in the context of belief revision, subjects are more inclined to abandon beliefs derived from the testimony of sources that are considered untrustworthy, e.g., a used car dealer, as compared to sources that are considered trustworthy, e.g., a policeman (Wolf et al., 2012). Recent studies that evaluate how subjects revise beliefs about the relative spatial positions of objects suggest that subjects perform such revisions by modifying a spatial mental model (Bucher et al., 2011; Krumnack et al., 2011a,b; Bucher & Nejasmic, 2012; Bucher, Nejasmic, Bertleff, & Knauff, 2013; Knauff et al., 2013; Mikheeva, Bucher, Nejasmic, & Knauff, 2013; Nejasmic, Bucher, & Knauff, 2013). In revising such spatial models in the face a newly introduced ‘fact’ statement that describes a relation between two objects (e.g., the orange is to the right of the pear), it has been shown that subjects have a strong and robust preference for relocating the object that appears as the grammatical subject (orange) in comparison to the grammatical object (pear) of the fact statement.

Here, we study the belief revision preferences within way-finding scenarios. Way-finding is a comparatively complex task, which can be divided into a number of different components. In the two experiments presented here, the focus is on uncovering the behavior of subjects when they are faced with partly erroneous route descriptions. The following example illustrates the kind of scenario that we investigate.

Imagine you are following a route according to instructions that include the positions of landmarks, and information regarding which direction to turn (right or left) when you reach a given landmark. You eventually get to the point where the following instruction should be applicable: “When the large white church appears on your left side, as you approach a fork in the road (T-junction), turn right.” But in this case, reality does not match with your expectations. Rather when you approach the fork, the church appears on the right, rather than the left. Faced with this situation, you must revise your beliefs in order to remain consistent, and your decision about how to revise your beliefs will (usually) determine the new route that you adopt in the hope of reaching your destination. In the present example, there are multiple ways of revising your beliefs, in order to make sense of the situation. Consider two:

1) You give up your belief that the initial route description is correct with regard to the position of the church. You ignore the fact the church appeared in an unexpected location, and decide to turn right.

2) You give up your belief that the initial route description correctly described the position of the church. However, you maintain the belief (implied by the initial route description) that you should turn in the direction that is opposite to the position of the church. Since you have now found the church on the right hand side, you decide to turn left.

What is the most likely choice for agents placed in the preceding situation? This is the main question that we attempt to answer with the experimental results described below. We also attempt to determine whether the behavior of subjects in situations such as the one just described is modulated by the semantic salience of the landmark that is found to be in an unexpected location. It is appropriate to note that our investigation bears a strong affinity to previous studies of both cognitive mapping and spatial updating, in those cases where subjects were placed in a situation of 'spatial mismatch', i.e., a situation where, subsequent to being trained to navigate a given stable environment, subjects are forced to

navigate the environment after some features of the environment have *changed* (cf. Dudshenko, 2010). The target of our investigation differs slightly from such work. Earlier work involving spatial mismatch has concerned itself with attempting to understand the manner in which subjects represent their spatial environment (e.g., Tolman, 1948), or with attempting to determine the type of cues that subjects use in judging their position relative to a target location (e.g., Srinivasan, Zhang, Lehrer, & Collett, 1996). Our inquiry differs slightly, since our primary concern is to understand how subjects revise their beliefs when they discover that they have incorrectly represented their environment (or incorrectly represented their location in the environment), and the mismatch between the subject's beliefs about the environment and its actual state is not plausibly regarded as a result of a change in the environment. So we are specifically interested in the process that philosophers have called "belief revision" (cases where an agent receives new information indicating that some of her present beliefs *are* and *were* incorrect) as opposed to "belief update" (cases where an agent receives new information indicating that the environment has changed, such that some of her present beliefs are no longer correct) (see Hansson, 2011).

We before proceeding, take note of an important point regarding our example above. This is that, from the standpoint of logic, an instruction with an antecedent concerning "when the large white church appears on your left side" has no bearing on what to do when the church is encountered on one's right. However, within the context where a subject is presented with a route description, which includes an instruction that features the preceding antecedent, we take that subjects adopt the expectation (i.e., belief) that the church will appear on the left, as they proceed according to the given route description. The same point applies in considering the tasks that we presented to subjects (which are described below).

Experiment 1: Erroneous route descriptions – Houses in virtual environments

The experiment was designed to investigate how individuals revise their beliefs during way-finding, and was kept as simple as possible. Participants first received a series

of four instructions, which were presented to subjects as a “route description”. One instruction might state, for example, “red house on the left, turn right”. In the *test condition (revision)*, participants were then presented with a T-junction, with a landmark positioned on the opposite side of the path from that specified in the *antecedent* of the corresponding initial instruction. For example, the red house appears on the right, and not the left. Our main question was: do participants turn in the direction prescribed in the consequent of the initially given instruction (and ignore the unexpected position of the landmark mentioned in the instruction’s antecedent)? If not, is there some other pattern to be found in their behavior? For example, do subjects behave in a manner consistent with alternative 2) of the example described above?

Experiment 1

Method

Participants. Twenty-four students (14 female; age: $M = 24.04$ years; $SD = 2.44$) from the University of Giessen provided informed written consent to participate. They were tested individually in a quiet lab room and received course credit for participation or a small financial compensation.

Materials, procedure, and design. Items consisted of verbal instructions relevant to proceeding through an environment, and presentation of a simulated T-junction to which subjects were expected and instructed to apply one of the previously learned verbal instructions. The verbal instructions consisted of four statements specifying whether to turn left or right at certain landmarks. The landmarks (presented in the same order across all items) were: a yellow house, a blue house, a red house, and a green house. The subsequently presented T-junction featured exactly one of these four landmarks (e.g., the red house), positioned at the left or the right side. Half of the items served as *control items* where the position of the landmark (left or right) at the simulated T-junction matched the verbal instructions. For instance, the instructions stated: “red house on the right” and the simulated T-junction featured the red house on the right. The *control items* allowed us to test whether participants successfully adopted beliefs in accord with the verbal instructions

and were able to make decisions in accordance with these instructions. The other half of the items were *revision items*, and were of central interest in our investigation. Within the revision items, the landmark appearing in the item was positioned on the opposite side of the T-junction from the position described in verbal instructions. Solving a revision item thereby required a revision of the subject's belief concerning how to proceed, once the landmark was encountered. An example item is depicted in figure 1.

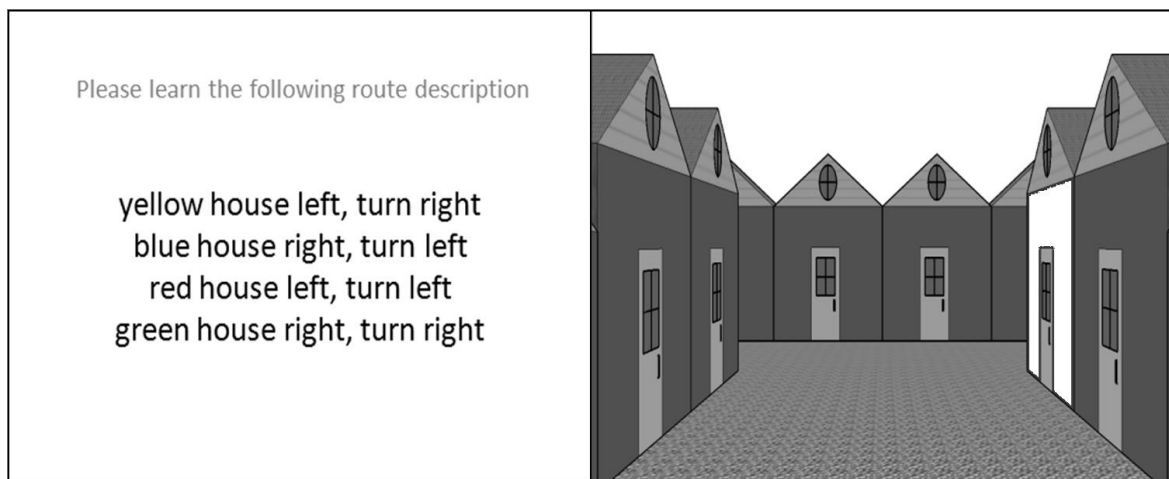


Figure 1. Verbal instructions (left) and a spatial way-finding scenario as presented in a revision trial (the white house on the right side represents the red house).

We investigated individuals' behavior with two types of descriptions: (1) *congruent* instructions (half of the items) in which the verbal instruction applicable to the encountered T-junction expressed (implicitly) that the respective landmark will appear on the same side of the path in which the participant should turn (e.g., red house on the left side, turn left), and (2) *incongruent* instructions (the other half of the items) in which the verbal instruction applicable to the encountered T-junction expressed (implicitly) that the respective landmark will appear on the opposite side of the path from direction to be turned (e.g., red house on the left side, turn right).

Participants were asked to learn the four verbal instructions and proceed (via button press) in a self-paced manner to the simulated T-junction (based on the virtual environment SQUARELAND; for details see Hamburger & Knauff, 2011). Within each item, participants

were asked to indicate (via a button press) which direction (left or right) he/she would like to turn.

Thirty-two experimental trials, preceded by six practice trials (not analyzed), were presented in a random order. Landmark position and the direction to be turned (according to the verbal instructions) were counter-balanced, as was the specific landmark appearing at the simulated T-junction. Route descriptions were generated with Microsoft PowerPoint® (Version 2007), and the simulated T-junctions with GoogleSketchUp 8.0 (Google®). Stimuli were presented and data (turn choices and decision times) recorded, using Superlab 4.0 (Cedrus Corporation, San Pedro, CA, 1999). The experiment was run on a custom personal computer (Windows XP) with a standard 19'' monitor. Participants provided answers using an RB-530 response box.

Results and discussion

Participants studied the route description for $M = 15.51s$ ($SD = 9.28$). Analyses of variance (ANOVAs) for turning direction, choice rates, and decision times (outliers above 30s were excluded from the analyses) were calculated. Based on the experimental design, the within-subject factors Task Type (control, revision) \times Verbal Instruction Type (congruent, incongruent) were submitted to the analyses. ANOVA for relative number (%) of turns in the prescribed direction of the verbal instruction (i.e., in accord with the *consequent* of the applicable instruction) revealed a main effect of Task Type, $F(1,23) = 19.93$; $p < .001$; $\eta^2_{part} = .464$, and a marginal interaction Task type \times Verbal Instruction Type, $F(1,23) = 3.876$; $p = .061$; $\eta^2_{part} = .144$.

A follow-up t-test comparing the overall percentage of turns into the prescribed turning direction showed that participants chose the prescribed turning direction significantly more often in the control tasks (88%; $SD = 16.78$), $t(23) = 4.363$; $p < .001$, than in the revision tasks (48%; $SD = 38.20$) which reflects a high correct performance in almost 90% of the control tasks, but suggests a different strategy for the revision cases. Further t-tests, comparing the percentage rates revealed no significant difference in the performance rates for congruent and incongruent instructions within the control cases ($p >$

.35). The essential (critical) decisions of the experiment were those made in the revision trials. Here we found a marginally significant difference in the relative number (%) of turns in the direction prescribed by the verbal instruction for congruent and incongruent revision items. The direction of the turns were more often in accordance with the verbal instruction in the congruent (54%; $SD = 41.15$) than in the incongruent condition (40%; $SD = 42.82$), $t(23) = 1.935$; $p = .065$. For example, given the congruent instruction “red house on the right, turn right”, and the confounding observation of the red house on the left, participants’ choice of which direction to proceed exhibited a slight tendency to turn right (i.e., in the direction prescribed). On the other hand, given the incongruent instruction, e.g., “red house right, turn left”, and the confounding observation of the red house on the left side, participants tended to turn right (i.e., contrary to the direction prescribed, and in the opposite direction of the landmark). Figure 2 depicts the means for the turn choice rates (turns as prescribed and turns contrary to prescribed) under the condition of congruent versus incongruent instructions.

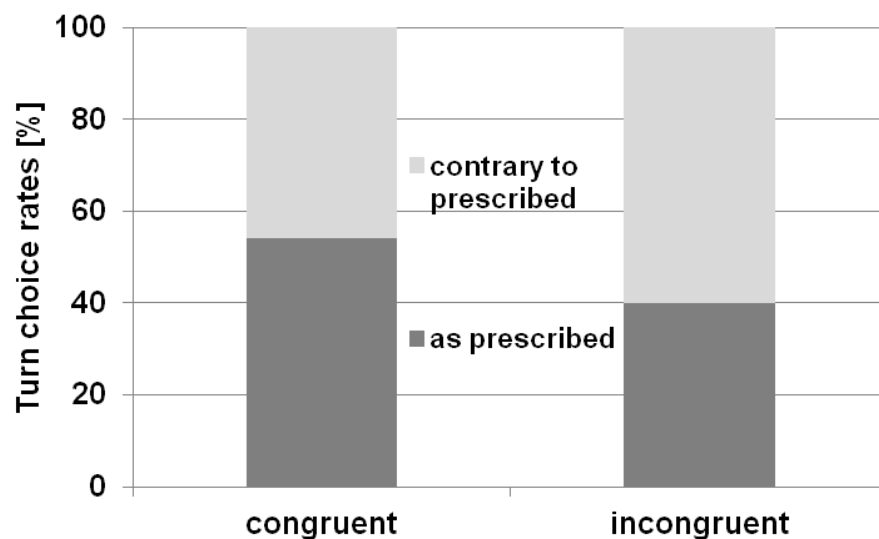


Figure 2. Mean turn choice rates [%] for revision items in the congruent and the incongruent instruction conditions (as prescribed; contrary to prescribed).

ANOVA for decision times for turns in the prescribed direction of the verbal instruction revealed a main effect of Task Type, $F(1,13) = 6.222$; $p = .027$; $\eta^2_{part} = .324$, no effect of Verbal Instruction Type and no interaction Task Type \times Instruction Type ($ps >$

.10). Follow-up t-test, comparing the decision times of control and revision tasks showed that the decisions of participants took longer in the revision cases (7.84s; $SD = 8.05$) compared to the control cases (2.87s; $SD = 1.53$), $t(19) = -3.064$; $p = .006$. The difference presumably reflects the different nature of the tasks. In a control task, subjects must simply take the correct turn as indicated by the applicable verbal instruction. In a revision task, subjects must decide how to proceed given the (implied) conflict between the applicable verbal instruction and the position of the relevant landmark.

Choice rates in the revision tasks were modulated by the instruction type. In response to congruent instructions, subjects have a slight tendency to stick to the prescribed turning direction (thereby ignoring the fact that the relevant landmark has appeared in an unexpected location). In response to incongruent instructions, subjects preferred to turn in the direction opposite from the actual position of the landmark, and thereby behave in accord with 2) in the example above. That is, they give up their belief that the initial route description correctly described the position of the applicable landmark. However, they maintain the belief (implied by the initial route description) that they should turn in the direction that is opposite to the position of the landmark.

Note that the landmarks used in Experiment 1 have a low degree of semantic salience. This fact may have facilitated the neglect of the landmarks in modulating the behavior of subjects within the test condition (revision). In our second experiment, we investigated whether the decision patterns found in Experiment 1 would persist in a modified situation where the landmarks possess a high degree of semantic salience. Our interest was to determine whether the semantic salience of landmarks would influence the behavior of subjects under conditions analogous to the ones explored within Experiment 1, e.g., because such landmarks are harder to ignore than common landmarks such as ordinary houses.

Experiment 2

In large part, the experiment resembled Experiment 1, with the important exception that the landmarks featured within the tasks were very well-known, including Big Ben and

the Eiffel Tower, rather than ordinary houses. The landmarks were also presented to subjects within a photorealistic virtual environment. Once again subjects received a series of four instructions, featuring (well-known) landmarks. One instruction might state, for example, “Big Ben left, turn right”. In the *test condition (revision)*, participants were then presented with a T-junction, and a landmark (e.g., Big Ben) positioned on the opposite side of the path from that specified in the antecedent of the corresponding initial instruction. For example, Big Ben appears on the right, and not the left. Our interest was to discover whether the patterns found in Experiment 1 would also be found here.

Method

Participants. A new sample of twenty-one students (17 female; age: $M = 12.96$ years; $SD = 2.41$) from the University of Giessen provided informed written consent to participate. They were tested individually in a quiet lab room and received course credit for participation or a small financial compensation.

Materials, Procedure, and Design. Items followed the same design as in Experiment 1: verbal instructions relevant to proceeding through a photorealistic environment, and presentation of a simulated T-junction to which participants were expected to apply one of the previously learned verbal instructions. The verbal instructions consisted of four statements specifying whether to turn left or right at respective landmarks. The landmarks (presented in the same order across all items) were: Big Ben, the Eiffel Tower, the Television Tower of Berlin, and the Leaning Tower of Pisa. Within the cover story, subjects were told that their task was to navigate a theme park which displays scale replicas of famous landmarks. The subsequently presented T-junction featured exactly one of these four landmarks (e.g., the Eiffel Tower), positioned at the left or the right side. Half of the items served as *control items* where the position of the landmark (left or right) at the simulated T-junction matched the verbal instructions. An example item is depicted in figure 3. In order to be assured that all of the chosen landmarks were of high semantic salience of landmarks, we relied on results from (Hamburger & Röser, in revision).

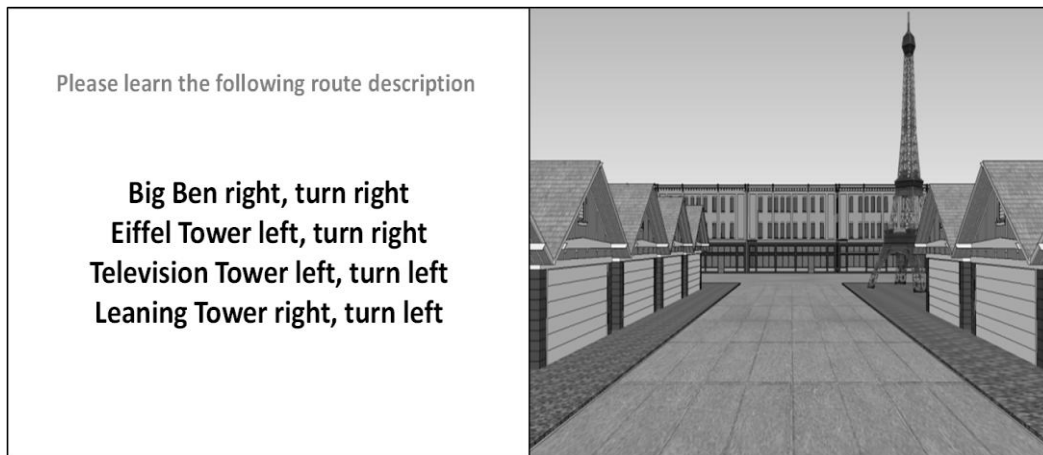


Figure 3. Verbal instructions (left) and a spatial way-finding scenario as presented in a revision trial.

As in Experiment 1, individual behavior was investigated under the conditions: (1) *congruent* instruction (half of the items) and (2) *incongruent* instruction (other half of the items). Stimulus material was again fully counter-balanced across the experiment. Item generation, presentation, as well as data collection were achieved by the same means and in the same manner as Experiment 1. Thirty-two experimental trials, preceded by six practice trials (not analyzed), were presented in a random order.

Results and discussion

Participants studied the instructions for 12.96s ($SD = 7.21$) on average. The same analyses were run as in Experiment 1. ANOVA for relative number (%) of turns in the direction prescribed by the verbal instruction revealed a main effect of Task Type, $F(1,20) = 23.022$; $p < .001$; $\eta^2_{part} = .535$, a marginally significant main effect of Verbal Instruction Type $F(1,20) = 3.081$; $p = .095$; $\eta^2_{part} = .133$, and a significant interaction Task type \times Verbal Instruction Type, $F(1,20) = 5.372$; $p = .031$; $\eta^2_{part} = .212$.

T-tests, comparing the percentage rates revealed no difference in the performance rates (88%; $SD = 13.88$) between congruent and incongruent instruction types in the control cases ($p > .35$). Regarding the essential decisions in the revision trials, the relative number (%) of turns in the direction prescribed by the relevant verbal instruction differed significantly between congruent and incongruent revision items. The direction of the turns

was more often in accordance with the verbal instructions in the congruent (51%; $SD = 41.15$) than in the incongruent condition (36%; $SD = 40.56$), $t(20) = 2.40$; $p = .026$. For example, given the congruent instruction “Eiffel Tower on the right, turn right”, and the confounding observation of the Eiffel Tower on the left, participants’ choice of which direction to proceed exhibited a very slight tendency to turn right (i.e., in the direction prescribed). On the other hand, given the incongruent instruction, e.g., “Eiffel Tower right, turn left”, and the confounding observation of the Eiffel Tower on the left side, participants preferred to turn right (i.e., contrary to the direction prescribed, and in the opposite direction of the landmark). Figure 4 depicts the means for the turn choice rates (turns as prescribed and turns contrary to prescribed) in revision items under the condition congruent versus incongruent instructions.

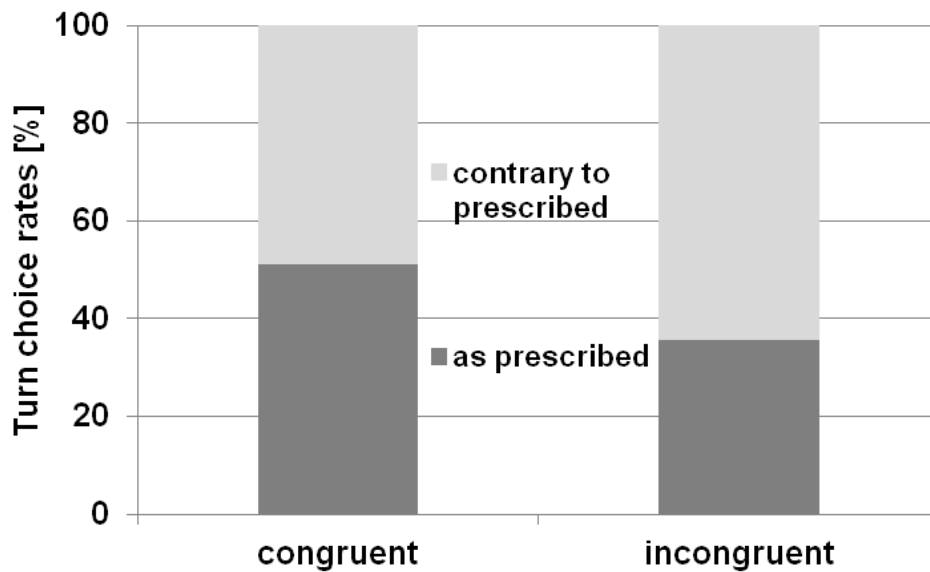


Figure 4. Mean turn choice rates [%] for revision items in the congruent and the incongruent instruction conditions (as prescribed; contrary to prescribed).

ANOVA for decision times for turns in the direction prescribed by the verbal instruction revealed a main effect of Task Type, $F(1,10) = 9.466$; $p = .012$; $\eta^2_{part} = .486$, no effect of Verbal Instruction Type and no interaction Task Type \times Instruction Type ($ps > .45$). Follow-up t-test, comparing the decision times of control and revision tasks showed that participants decisions took longer in the revision cases (5.23s; $SD = 2.99$) compared to

the control cases (3.76s; $SD = 1.86$), $t(17) = -2.174$; $p = .044$. Again, the difference presumably reflects the different nature of the tasks. In the control task, subjects must simply take the correct turn as indicated by the applicable verbal instruction. In the revision task, subjects must decide how to proceed given the conflict between the applicable verbal instruction and the observed position of the relevant landmark.

Finally we note that the decision pattern exhibited in Experiment 2 mimics the pattern found in Experiment 1, suggesting that participants applied the same revision principle in scenarios with landmarks with low and with high semantic salience.

General discussion

When one receives conclusive evidence for a statement that conflicts with what is currently believed, one must revise one's beliefs on pain of inconsistency. Abstract conditional and relational reasoning problems have provided the most popular test beds for the investigation of human belief revision (Revlis et al., 1971; Elio & Pelletier, 1997; Wolf et al., 2012; Knauff et al., 2013). The present paper introduces the study of belief revision in the course of way-finding. This represents a natural extension of past studies, inasmuch as belief revision is often required in the course of way-finding. As a starting point, we conducted two experiments that explore participant behavior in situations where a previously learned route description does not match the actual environment. In both experiments, the high performance accuracy of participants in the control trials provides strong evidence that the content of the verbal instructions, as encoded by subjects, is available from memory. The revision trials, on the other hand, provide insight about which pieces of information were preferably given up and which ones retained, in the case of conflict between the applicable verbal instruction and the observed position of the relevant landmark. We assume that these decisions were based on the best available information from memory.

Within revision trials, in both of the experiments described here, we observed distinct patterns of behavior in the case of congruent and incongruent instructions. This suggests that the decisions about what beliefs to maintain and reject are influenced by the

way the participants encode given instructions. When the side of the landmark position is congruent with the prescribed turning direction, participants exhibit a very slight preference to proceed in accordance with the (consequent of) the provided verbal instruction. With incongruent instructions, participants preferred to turn in the direction contrary to consequent of the verbal instruction. The behavior of subjects, in the case of incongruent instructions, may thus be explainable by supposing that subjects engage in reasoning of the sort described within 2) in the example above: They give up their belief that the initial route description correctly described the position of the applicable landmark, but maintain the belief (implied by the initial route description) that they should turn in the direction that is opposite to the position of the landmark. It is also possible to explain the pattern of responses by supposing that the precise content of the relevant instruction was better remembered in the case congruent instructions. So faced with the misplaced landmark in the congruent condition, subjects respond by choosing to proceed in a random direction (or by some arbitrary decision process), since they were unable to formulate a cogent strategy for dealing with the situation. On the other hand, for incongruent instructions, it is possible that subjects were unsure of the precise content of the relevant instruction, and so fell back to a particular consequence of the instruction, namely: *turn into the opposite direction of the landmark* (cf. Hamburger, Dienelt, Strickrodt, & Röser, 2013).

In the past, much research has been dedicated to the question of what factors enable successful way-finding: What are the features of a “good” landmark? How is multi-modal information integrated during navigation? Such research focuses on discovering how information is used for finding a way (e.g., Caduff & Timpf, 2008). Our combined approach goes beyond that. We consider the cognitive processes that operate on already integrated representations, and consider how these representations are adapted and modified in the light of conflicting information.

The experiments presented here provide a first step in answering important questions about the revision of beliefs in the course of way-finding. Moreover, the paradigm that we have employed is amenable to variations. Here we kept the simulated

environment quite simple, and only considered a variation in the semantic salience of the landmarks that appeared to subjects. Other variations may be investigated within further studies. For example, the paradigm can be adapted to present subjects with additional information about the source of the given route descriptions (e.g., a random pedestrian on the street, a friend, a taxi driver, Google maps, etc.), and/or about the conditions under which the route description was provided (e.g., the source was in a rush, or the source has a strong interest that you find your way). It would, of course, be worth investigating the extent to which the patterns exhibited in the experiments reported here result from the use strategies that are quite general (e.g., a general purpose strategy applicable to resolving communicative inconsistencies). And there are many further questions within the area that should be investigated. To name just a few: in what way does background knowledge influence the perseverance of a belief (e.g., that churches as potential landmarks usually occupy a central location in a village)? Similarly, what role do attributions play in decisions to revise beliefs in various ways (e.g., internal vs. external attribution: “the route description is erroneous” vs. “I went the wrong way”)?

Way-finding and orientation within our immediate spatial surround (e.g., finding information with one’s mobile phone, tablet PC, on the web, or just finding a paper on one’s office desk among several large piles of papers) requires sophisticated mental processes whose nature is rarely the subject of careful reflection. However, upon just a little consideration, it is obvious that we are regularly confronted with new information that contradicts our beliefs, and we revise our beliefs in order to navigate our environment. In this position paper, we have exemplified research in the intersection of two research fields of Cognitive Psychology (namely, belief revision and way-finding), and suggested the fruitfulness of further research in this area.

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Chapter 11

A model for relational reasoning as verbal reasoning¹¹

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Abstract

Deductive reasoning is an essential part of complex cognition. It occurs whenever human beings (or machines) draw conclusions that go beyond what is explicitly provided. Reasoning about spatial relations is an excellent test bed for the assessment of competing reasoning theories. In the present paper we show that such competing theories are often less diverse than one might think. We introduce an approach for how relational reasoning can be conceived as verbal reasoning. We describe a theory of how humans construct a one-dimensional mental representation given spatial relations. In this construction process objects are inserted in a dynamic structure called a “queue” which provides an implicit direction. The spatial interpretation of this direction can theoretically be chosen freely. This implies that choices in the process of constructing a mental representation influence the result of deductive spatial reasoning. To derive the precise rules for the construction process we employ the assumption that humans try to minimize their cognitive effort, and two cost measures are compared to judge the efficiency of the construction process. From this we deduce how the queue should be constructed. We discuss empirical evidence for this approach and provide algorithms for a computational implementation of the construction and reasoning process.

Introduction

Imagine you are reading a newspaper. In an article about the financial crisis you read that the stock price of bank A is higher than the stock price of bank B. Later in the article you learn that the stock price of B is higher than that of bank C. For most people, it is quite easy to mentally rank the three banks into one single order and to read off from this order that the stock price of bank A is higher than that of bank C. The task is rather easy, but, imagine that you receive the information in a different order e.g., B higher than C, A higher than B, or with other relational expressions, e.g., A higher than B, C lower than B. Or imagine that you have information not just about three banks but many others A, B, C, D, E, etc.? And now imagine that this is not a study in the psychological lab, but you are an actual stock broker and you can really lose a lot of money in just a few milliseconds.

Our example demonstrates that the cognitive process of inferring new information from information that is explicitly provided is a vital and indispensable part of problem-solving and decision-making. Understanding how humans draw inferences is an important field in the area of complex cognition research (Sternberg & Ben-Zeev, 2001) and studies in this field can even help to understand actual problems of our daily life (for a reasoning study on the cognitive aspects of the financial crisis see Knauff, Budeck, Wolf, & Hamburger, 2010). Another point is that relational expressions seem to be one of the most essential mental entities (Halford, Wilson, & Phillips, 1998; Goodwin & Johnson-Laird, 2005; Hummel & Holyoak, 2005). In a recent article entitled “Relational knowledge: the foundation of higher cognition” Halford, Wilson, and Phillips (2010) reported accumulating evidence on the nature, function and acquisition of relations and their crucial role in higher cognitive processes. In their review the authors show that relations play a vital role in reasoning, categorization, planning, and language. Relations are omnipresent in our daily life: in the stock prices example, for instance, differences between the banks are represented by spatial relations such as higher and lower. Other examples are:

Person A is smarter than Person B, X loves Y, City A has more citizens than City B, marriage is before divorce, global warming is more dangerous than most people think; computer scientists are as smart as psychologists, the earth-quake came earlier than the Tsunami; Barack Obama is more popular than George W. Bush was, Wolfgang Amadeus Mozart was the son of the bookbinder Johann Georg Mozart. From a formal point of view, a relation can have many arguments, but in our daily life, they seldom take more than three arguments (“The professor gave the book to the student”), and most often even just two entities (Goodwin & Johnson-Laird, 2005). The important point, however, is that relations are around almost everywhere and that it is difficult to see how we could solve complex daily-life problem, without the use of relations and the comparison of different alternatives. Such relational inferences seem to be quite easy, but, firstly, they often are not, and, secondly, even when they are easy to perform that does not mean that the underlying cognitive processes are easy to understand.

In the following paper we explore human reasoning with binary relations and how the underlying cognitive processes can be algorithmically reconstructed. All of our relations have in common that they are linear ordering relations, which means in particular that they are transitive. This fact allows us to create the underlying linear order between the objects featured in relational expressions. We demonstrate our approach by means of spatial relations between fruits (imagine them lying on a table). This is done just for the sake of easy illustration, but it should be clear, that the postulated mechanisms are much more universal. They are not limited to specific entities or to a specific subset of linear (transitive) relations. The bank stock prices, for instance, can be easily modeled in the framework, too! So, consider the following two sentences, also called premises.

Example 1:

1. The apple is to the left of the mango.
2. The mango is to the left of the pear.

These premises allow us to create a linear order of the objects named in the premises, apple–mango–pear. This order enables us to draw conclusions about information not directly given in the premises: we can infer that the apple is to the left of the pear. The ability to infer information about relations between objects not explicitly expressed by the premises is the subject of theories about relational reasoning (cf. Johnson-Laird & Byrne, 1991; Goodwin & Johnson-Laird, 2005, chap. 5). The bases of such inferences are mental representations that reflect information conveyed verbally by the premises. There are several theories on how this is accomplished (cf. Johnson-Laird & Byrne, 1991, chap. 5; Goodwin & Johnson-Laird, 2005; Knauff, 2009a,b). They differ in the postulated underlying mental representations and the computational processes that work on these representations. In one theory, it is believed that people think deductively by applying mental rules which are basically similar to rules in computer programs. In the other theory, deductive reasoning is conceived as a process in which the reasoner constructs, inspects, and manipulates mental models. The rule-based theory is usually

described as a syntactic theory of reasoning, as it is based on the form of the argument only, whereas the mental models theory is seen as a semantic theory, because it is based on the meaning (the interpretation) of the premises. The rule-based theories are primarily represented by the work of Rips (1994) and Braine and O'Brien (1998). Relational versions of the account have been developed, for instance, by Hagert (1984) and van der Henst (2002). The main claim of this account is that reasoners rely on formal rules of inference akin to those of formal logic, and that inference is a process of proof in which the rules are applied to mental sentences. The formal rules govern sentential connectives such as "if" and quantifiers such as "any", and they can account for relational inferences when they are supplemented with axioms governing transitivity, such as: for any x , y , and z , if x is taller than y and y is taller than z , then x is taller than z . The rules are represented in long-term memory and the sequence of applied rules results in a mental proof or derivation that is seen as analogous to the proofs of formal logic (Rips, 1994).

The theory of mental models has been developed by Johnson-Laird and colleagues (Johnson-Laird, 1983, 2001, 2006; Johnson-Laird & Byrne, 1991). The latest version of the theory of relational reasoning based on mental models has been explicated in Goodwin and Johnson-Laird (2005). According to the mental model theory, human reasoning relies on the construction of integrated mental representations of the information that is given in the reasoning problem's premises. These integrated representations are models in the strict logical sense. It is a mental representation that captures what is common to all the different ways in which the premises can be interpreted. It is a "small scale" representation of how "reality" could be – according to what is stated in the premises of a reasoning problem. Based on the MMT, Knauff, Rauh, Schlieder, and Strube (1998) propose three stages involved in the relational reasoning process: a construction phase, during which reasoners construct a mental model, reflecting the information of the premises, an inspection phase, during which the model is inspected for implicit information of the premises, and a variation phase, during which alternative models are constructed and investigated concerning their compatibility with the information given by the premises, if

necessary, resulting into falsification of the preliminary mental model, constructed during the first phase.

The starting point of our paper is that the long-lasting dispute between rule-based and model-based theories is quite unproductive, because no single account can explain all of the experimental findings in reasoning research (e.g., Oberauer, 2006; Goel, 2007; Stenning & van Lambalgen, 2008; Knauff, 2009a, 2009b). Another reason for our research is that the seemingly helpful distinction between models as semantic and rules as syntactic approaches also cannot be upheld from a formal point of view, because Stenning and collaborators have shown the abstract equivalence of all the main psychological competence theories of human reasoning (Stenning & Oberlander, 1995; Stenning, 1998). Their apparently contrasting representations are computationally equivalent for the kind of data presented in the literature (Stenning & van Lambalgen, 2008). In a similar vein we interpret the work by Polk and Newell (1995), who point out that the model-based deduction process, does not necessarily require deduction-specific, non-linguistic mechanisms to operate on internal representations. Especially in reasoners that are not specifically trained on deductive reasoning more general cognitive mechanisms might guide the reasoning process. They introduced an approach, called verbal reasoning that assumes the cognitive processes in deductive reasoning to be based upon the same processes as language comprehension and generation. Verbal reasoning describes reasoning as transformation of verbal information provided by the premises of an inference problem. Linguistic skills operate in order to encode and re-encode a reasoning problem until the conclusion becomes obvious or until the reasoner gives up. Polk and Newell (1995) hypothesize that when task-relevant information is provided verbally, the crucial role in reasoning is played by the verbal processes of encoding and re-encoding accordingly and that inferences follow immediately from the encoded information. The computational approach presented by Polk and Newell accounts for many experimental findings in a number of deductive reasoning tasks, among them reasoning with relations.

In the following, we sketch how relational reasoning can be conceived in Polk and Newell's framework of verbal reasoning. In particular, we propose new theoretical

assumptions for the special case of reasoning with spatial relations. The key assumption is that the process of constructing a mental representation – a mental model – from the premises influences deductive spatial reasoning. This implies that the process of encoding information is critical for the result of the reasoning process. We discuss empirical evidence as well as a computational implementation of the encoding and reasoning process.

A cognitive model

We are proposing a theory on how humans create a mental model from a set of (spatial) relations. The theory consists of two parts: the general structure of models and the most efficient process of constructing these models.

The first part lists basic assumptions of what properties the mental model is supposed to have, thereby defining the general structure of the model. The second part is based on the idea of cognitive efficiency. The idea is that humans try to minimize their cognitive effort and thus a computational cost measure can help to estimate the efficiency of an inference. From this approach we derive how a mental model should be constructed within the framework laid out in the first part. This mental model can then be used to reason about (spatial) relations and its properties imply consequences for the reasoning process.

Basic structural assumptions for the cognitive model

Since we consider arbitrary transitive relations as the basis for the model we assume that models consist of a “queue” of objects and an interpretation what this queue represents. The queue describes in which order the objects are aligned but what this order represents depends on the relation that is considered. It can range from stock prices arranged from highest to lowest, over the population of cities from smallest to largest, to alignments of objects in space from left to right. So while the order of a queue is implicit the interpretation of the order is not. The queue is constructed by forming links between objects. The links signify which objects follow each other in that ordered arrangement.

These links between the objects are one directional which means that when inspecting the queue we can move from one object to the next object in the queue but not to the preceding object. To access the queue one needs to access the first element of the queue. Therefore the beginning of the queue is marked by a start pointer, marking the starting point. The queue can be accessed from this starting point which is directed at the first object. From there all other objects in the mental model can be reached by following the links between objects. This amounts to the following assumptions about the queue

- 1^{qu} There exists a starting point or first object.
- 2^{qu} Each object is linked to the next object in the linear order. Only the last object is not linked to other objects.
- 3^{qu} While this structure has an implicit direction, the interpretation of this direction depends on the context.

The starting point can also be considered a link. This is due to the fact that one has to know how the queue starts in order to access it. Therefore knowing which object is the first constitutes a link, connecting the start of the queue to that object. This structure is not limited to portraying spatial relations but a model constructed this way can be used to describe any linear order.

Construction of a queue from spatial information

The question now is how a mental model is constructed from the premises of a reasoning problem. How are objects featured in the premises inserted in the queue? In this process the first premise that is considered has a special function and dominating effect on the construction of the rest of the arrangement. We consider the first premise independently of the following premises and postulate the following two rules for the construction process.

- 1^{fp} The first object inserted in the queue is the starting point of the queue.

2^{fp} The second object is linked to the first object. The relation between the first and the second object thereby creates the interpretation of the link and the implicit direction of all the following objects in the queue.

If we know, for example, that the object which has been inserted secondly is supposed to be to the right of the first (starting) object, then the link is interpreted as “to the right”. When we look at our example again from the introduction this results in two options for the first premise: “The apple is to the left of the mango.” We can choose the apple as the starting point (marked by the asterisk) and insert the mango thereafter

(1) apple* → mango

The implicit direction of the queue is interpreted as moving from the leftmost object to the right. Theoretically we could also use the mango as a starting point (marked by the asterisk) inserting the apple thereafter. The corresponding model could be depicted as follows:

(2) apple ← mango*

In this case the implicit direction of the queue is interpreted as moving from the rightmost object to the left. So even though the premise describes only one arrangement of fruits there are two options for representing this arrangement in our queue. However, with a sentence like: “The apple is to the left of the mango.” we can assume that only model (1) will be used with the choice putatively influenced by cultural and/or biological aspects. There is vast evidence for a left to right bias on spatial routines (Tversky, Kugelmass, & Winter, 1991; Chatterjee, Southwood, & Basilico, 1999; Maass & Russo, 2003; Dobel, Diesendruck, & Bölte, 2007). Cross-cultural studies suggest that this bias arises from the scanning habit induced by reading and writing direction predominantly used within a certain culture (e.g., Chan & Bergen, 2005; Spalek & Hammad, 2005; Dobel et al., 2007)

and that this cultural bias influences spatial representations of objects. Another view is that the left to right bias arises from aspects fundamentally implemented in the functional architecture of our brains (e.g., Levy, 1976; Beaumont, 1985; Chatterjee et al., 1999; Chatterjee, 2001 for some culture-independent preferences in spatial reasoning, see for instance, Knauff & Ragni, 2011).

The results of an early study by De Soto, London, and Handel (1965) indicate that the left end of a linear order is the preferred starting point (in our example the apple). Given a statement about a relation between two people, participants were asked to write down the names in two of four boxes and the results reflect a preference for working from left to right (De Soto et al., 1965).

In a recent experiment conducted in our lab, we asked participants to arrange colored wooden blocks (red, green, blue, yellow) according to a description given by two premises with colors (red, green, blue, yellow) mentioned in the premises representing respective blocks. We found that subjects tended to start with the block first named in the (first) premise. So for both sentences “Red is to the left of blue” and “Red is to the right of blue” the red block was inserted first and then the blue block was placed accordingly. The experiment will be reported in detail elsewhere (Bucher, Krumnack, Nejasmic, & Knauff, in preparation).

For a sentence like: “The apple is to the left of the mango.” the order of the objects in the sentence and their left-to-right order in the described spatial arrangement coincide. Therefore, starting with the first object in the sentence, reasoners would presumably build the model from the left to the right meaning model (1) would be constructed.

However, with a sentence such as: “The mango is to the right of the apple.” the situation is less clear. Here the object which is named first is supposed to be on the right side of the arrangement while the second object is on the left. Reasoners could either insert the objects in the order in which they appear in the sentence, that is from the right as in model (2) or they could arrange the objects from left to right as in model (1). In both cases they follow a left to right preference. Once the interpretation of the implicit direction of the queue is fixed by inserting the second object the rest of the objects are inserted

according to this interpretation. This amounts to the following options for inserting objects in an existing queue from the second premise:

- 1^{ins} One object (the reference object) of the premise has to be found in the queue.
- 2^{ins} (a) If the new object is to be placed behind this object (with regard to the implicit direction of the queue) it can be either inserted into the queue directly behind the object or at any point further to the end of the queue.
(b) If the new object is to be placed in front of the object (with regard to the implicit direction of the queue) it can be either inserted into the queue directly in front of the object or at any point further to the beginning of the queue.

The question is which of the options outlined in 2^{ins} is used when inserting an object into the queue. Where exactly is the object inserted? To determine this we use the idea of cognitive efficiency which suggests, that humans try to minimize their mental effort. Given e.g., working memory capacity limitations, a reasonable goal would be to minimize usage of available resources in order to maximize performance (e.g., Süß, Oberauer, Wittmann, Wilhelm, & Schulze, 2002).

Insertion into the model

There are two kinds of operations to be performed when inserting an object into an existing queue (after the reference object is found):

1. Movement through the queue.
2. Creation of new links.

The cost of the movement through the queue can be calculated as the number of objects that were passed. Also, accessing the starting point from any other object than the

first object in the queue counts as movement. For the creation of links we can count the number of new links that need to be created when an object is inserted into the queue. Let us consider the computational cost that results from inserting a new object into the queue between two objects that are linked. Say, for example, we want to insert pear between apple and mango in the following queue:

... → apple → mango → ...

To insert a new object between two existing objects in the queue the first object, which was linked to the second object before, now has to be linked to the new object. The new object has to be linked to the second object. In our example apple needs to be linked to pear and pear to mango resulting in the following queue:

... → apple → pear → mango → ...

This process of inserting an object between two objects in a queue requires forming two new links. If the object is inserted at the beginning of the queue the starting point needs to be redefined which we will consider as creating a new link. So the process of inserting an object at the beginning of an existing queue also requires forming two new links. Inserting an object at the very end of the queue, following the last object in the queue, only requires creating one new link, no existing links have to be changed. But we have to move through the entire queue to get to the last object. We assume that the queue is constructed in the most efficient way. So the question to answer is: what is efficient?

We will look at two different cost measures that allow us to judge how to create the queue efficiently, that is, where to insert an object into an existing queue and compare the predictions that can be derived from the two cost functions. Firstly we will consider what happens if both kinds of operations are treated the same way, that is, both are assigned the same cost. This amounts to a complexity measure that is used as a standard in

computational complexity estimation. Secondly we introduce a cost measure where we assign a higher cost to creating a link than to moving through the queue.

Computational complexity estimation

In Computer Science the efficiency of algorithms is usually assessed by adding the costs of operations necessary to execute the algorithm. In this context, one often uses a uniform cost measure since the real costs are often not known nor are they important in an asymptotic analysis. We adopt here a similar strategy. In this specific case that implies creating one link and moving one object through the queue produce the same cost. A similar complexity measure has been used by Ragni, Knauff, and Nebel (2005). We do not imply that this is necessarily a cognitively adequate cost measure but it seems a good default comparison since it does not make any assumptions about different cognitive costs of operations. By comparing measures that make such assumptions with this standardized default it can be seen whether those measures perform better or worse. This should give an indication of how reasonable those assumptions are.

Using this standard computer science cost measures we look at the possibilities from above, 2^{ins} (a) and (b), for insertion into an existing queue. Which of these options is the most cost efficient? When inserting a new object behind an object of the queue as in 2^{ins} (a), and we insert it directly behind the object, we have the cost of creating two links (see above) unless we are at the end of the queue in which case only one new link is required. If we want to insert the object further down the queue we have to move to that point within the queue and the cost of moving through the queue have to be added to the cost of creating new links. And moving one object down the queue costs as much as creating a link. So inserting a new object after an object further down the queue is always at least as expensive as inserting it right behind the reference object even when inserting it at the end of the queue. If the end of the queue is more than one object away, the cost of moving through the queue and creating the link will be even higher than the cost of just inserting the new object right behind the reference object. And since there is no way of

knowing how far away the last object is, the cost efficient solution is to insert the new object right behind the reference object.

When inserting a new object in front of an object as in 2^{ins} (b), the same cost results with respect to the links being formed for inserting the new object right in front of the reference object and for inserting it at the beginning of the queue. In both cases two new links need to be created, if we insert the object at the beginning of the queue one of the new links that need to be created is the starting point. However, when we insert the object at the very beginning the starting point of the queue has to be accessed, so we have a movement which means one extra step. If the object is inserted at any other point of the queue the cost is higher since we first have to move to that point from the beginning of the queue. So using this cost analysis it would be most efficient to insert the object directly in front of the reference object. Based on this analysis we derive cost efficient rules for inserting nodes into a list:

- 1^{CC} If the new object has to be placed behind an object of the list it should be inserted into the list *directly behind* the object.
- 2^{CC} If the new object has to be placed in front of an object of the list it should be inserted into the list *directly in front* of this object.

If we apply these rules to the second premise of example 1 from the introduction (starting with model (1), (2), respectively, from Section 2) we create one of the following two models depending on the direction of the queue¹².

(3) apple* → mango → pear

(4) apple ← mango ← pear*

¹² As discussed in Section 2, we assume that the queue would generally be constructed from left to right for this specific case. The other direction is included to allow a comparison of cost and a complete theoretical evaluation. Both directions will therefore be covered in this section about cost estimation.

While the results look similar, the costs for building these models differ. The cost for inserting the two objects from the first premise into a new queue are always the same and therefore do not need to be considered. But what are the costs for including the information of the second premise into the model? In case (3) we use rule 1^{CC} but since we insert the object at the end of the list, only one more link needs to be created. In case (4) however, we use rule 2^{CC} which in this case amounts to inserting the object (pear) at the beginning of the queue. So we need to redefine the starting point and create a new link. This results in creating two new links. So the cognitive cost for building the first model is lower. Note that in both cases no movement through the queue is necessary. Let us look at another example that is not quite as simple:

Example 2:

- 1 The apple is to the left of the mango.
- 2 The apple is to the left of the pear.

Here the premises describe an indeterminate order: there are two possible orders of these three fruits: apple–mango–pear and apple–pear–mango. So the question is, whether one of these orders is preferred over the other? Knauff, Rauh, and Schlieder (1995), Rauh et al. (2005), Jahn, Knauff, and Johnson-Laird (2007) have empirically shown that such preferences exist in human reasoners. Since the first premise is identical to the one in example (1) with the determinate order we receive the same two options for models when applying the rules for the first premise. If we apply the rules of insertion to the second premise we get one of the following models, using rule 1^{CC} and rule 2^{CC} respectively.

- (5) apple* \rightarrow pear \rightarrow mango
- (6) apple \leftarrow pear \leftarrow mango*

Again we see no difference between the models even though the arrangement is indeterminate, so more than one model could be created. However, model (5) was built

using rule 1^{CC} , model (6) following rule 2^{CC} . Nevertheless, the insertion of the last object has the same computational cost in both of these models as in both cases two links have to be created.

Alternative cost measure

We now introduce an alternative cost measure for which the main assumption is that as few new links as possible should be formed to minimize cognitive work. This implies that if it can be avoided, an existing link should not be broken. As a cost measure we therefore use primarily the number of links that need to be formed. If this does not show any difference between the options the required movement through the queue is used as a secondary cost measure. This reflects that forming a link is supposed to require more cognitive effort than moving through the queue, no matter how far we have to move through the queue. Because of the structure of a model laid out in the assumptions 1^{qu} and 2^{qu} above, at the end of the construction process the complete mental model has as many links as there are objects in the model (including the start pointer as a link). Since the final number of links in a mental model is fixed, costs can only be reduced by altering as few links as possible during the construction process. Therefore when inserting new objects it is most cost efficient to create just one new link and to not change any existing links.

Inserting an object at the very end of the queue, following the last object in the queue, only requires creating one new link, no existing links have to be changed. We have to move through the entire queue to get to the last object but in this cost measure the cost of moving through the queue can be disregarded in this estimation. Using this information we will now estimate the cost created by the insertion options described in 2^{ins} (a) and (b). As stated before cost will be measured primarily as the number of links that need to be formed. Only if two options require the same number of links to be formed will we use the number of steps moved through the queue as a secondary cost measure.

Let us first look at option 2^{ins} (a): if the object is inserted between two objects of the queue two new links need to be formed. If the object is inserted at the end of the queue, only one new link needs to be formed. So in case 2^{ins} (a) it is most cost efficient to insert

the object at the very end of the queue. Now we consider 2^{ins} (b): the new object can only be inserted between two objects or at the starting point of the queue. Since we consider the starting point a link to the beginning of the queue both options require two new links to be formed. So it is more cost efficient to not move around the queue but to insert the object directly in front of the found object. Using this analysis we postulate the following rules:

- 1^{AC} If the new object is to be placed behind an object of the queue it will be inserted at the end of the queue.
- 2^{AC} If the new object is to be placed in front of an object of the queue it will be inserted into the queue directly in front of this object.

If we apply these alternative rules of insertion to the second premise from example 2 we get the following models:

- (7) apple* \rightarrow mango \rightarrow pear
- (8) apple \leftarrow pear \leftarrow mango*

Here we see a difference between the models constructed from the indeterminate description depending on the implicit direction of the queue and on the place of insertion. Because the two queues have opposite interpretations of the implicit direction different rules are applied to form the queues. There is also a difference in the cost for building these models. In (7) we were able to apply rule 1^{AC} , again creating only one new link. In (8) we needed to apply rule 2^{AC} , redefining the starting point, creating two new links. So the costs for creating the last model (8) are higher than the ones for creating model (7).

The models illustrate that rules based on a classic computational cost measure produce partly different results than our rules based on the alternative cost measure. Model (7) differs from model (5) above while model (6) is similar to model (8). So if the queue is constructed from left to right, we have different predictions on how the model should be constructed. For completeness we could also consider assigning higher cost to movement

through the queue than to creating a new link. However, this would lead to the same predictions and models as the classical computer science cost measure, which makes it redundant to discuss this case in detail.

Empirical evidence

Since the two cost measures lead to different rules which result in different models to be constructed the question is which rules predict human behavior better. Or differently phrased: is it justified to assume that forming a link is more cost intensive than moving through the queue? If not, the traditional computational complexity measure should lead to better predictions than our alternative cost measure. To answer these questions we report an experiment that implies that rules derived from our alternative cost measure predict human behavior better than the rules derived from the traditional computer science cost measure. In this experiment we investigated what kind of mental model participants construct when they are faced with indeterminate problems as in example (2) that allowed more than one model to be constructed. The problems were designed to differentiate between the two discussed options for construction rules. We only use the relation “left of” because, as discussed in Section 2, we can be relatively certain that the subjects will actually construct the queue from left to right for this relation.

Material and method. Thirty-five participants (three male; age: $M = 22.4$; $SD = 3.2$) from the University of Giessen had to solve 16 determinate (like in example 1) and sixteen indeterminate problems (like in example 2). The three-term problems had two premises each and we used only the relation “left of”. The problems were presented to the participants in a random order on a computer screen. Each premise was presented sequentially (in a self-paced manner). Subsequently, after participants had read the premises, a conclusion was presented and the participants were asked if this conclusion was correct or not by indicating their choice by pressing the respective response button (“yes” or “no”) with the left or right hand, accordingly. Locations of “yes” and “no” buttons were counterbalanced across participants. For determinate problems the conclusion was either true or false, thus the correct answers were “yes” for

determinate/valid items and “no” for determinate/invalid items. For indeterminate problems we used two different types of conclusions which could either hold in a model constructed according to rule 1^{AC} or in a model constructed according to rule 1^{CC} (see figure 1 for examples).

1. The apple is to the left of the mango.
 2. The mango is to the left of the kiwi.
- C1: The apple is to the left of the kiwi. (true)
C2: The kiwi is to the left of the apple. (false)
-
1. The apple is to the left of the mango.
 2. The apple is to the left of the kiwi.
- C1: The mango is to the left of the kiwi. (true according to rule 1AC)
C2: The kiwi is to the left of the mango. (true according to rule 1CC)

Figure 1. Top: A determinate item and with the two possible conclusions C1 and C2. Bottom: An indeterminate item with the two possible conclusions C1 and C2 .

Please note that indeed both types of conclusions from indeterminate descriptions were valid in a logical sense. However, due to constructing the model by applying a preferred rule (1^{AC} or 1^{CC}), participants were expected to accept conclusions that hold in models constructed by the preferred rule and (mistakenly from a logical point of view) reject conclusions that hold in models as would have been constructed by the not preferred rule. The purpose was to gain insight whether rule 1^{AC} or rule 1^{CC} was preferably applied for constructing the model. The correct answer was “yes” for both, indeterminate/1^{AC} and indeterminate/1^{CC} items. Percentage of correct answers and corresponding decision times were recorded. All stimuli were generated and presented using Superlab 4.0 (Cedrus Corporation, San Pedro, CA, 1999) with an RB-530 response pad running on a standard personal computer (2.80 GHz) with a 19“ monitor.

Results and discussion. Separate ANOVAs for the percentage of correct responses and decision times for correct responses (determinate/valid, determinate/invalid, indeterminate/1^{AC}/valid and indeterminate/1^{CC}/valid) were calculated. Level of significance was 5%. ANOVA of the percentage of correct responses yielded a significant

main effect, $F(2, 32) = 54.79, p < .01$. Percentage of correct responses of determinate/valid and determinate/invalid items did not differ ($p > .75$). The high percentage of correct responses for the determinate items ($M = 92.19; SD = 11.14$) indicate that the participants understood the task and were able to perform well. Because of the reasons discussed in Section 2 and because the determinate items are more efficiently constructed from the left to the right for both cost functions we assume that they were indeed constructed from left to right. We also assume that the indeterminate items were constructed from left to right as well, since the decision has to be made directly after reading the first premise before knowing whether the item is determinate or indeterminate. We find a higher percentage of correct responses for indeterminate/ 1^{AC} items compared to indeterminate/ 1^{CC} items (see figure 2).

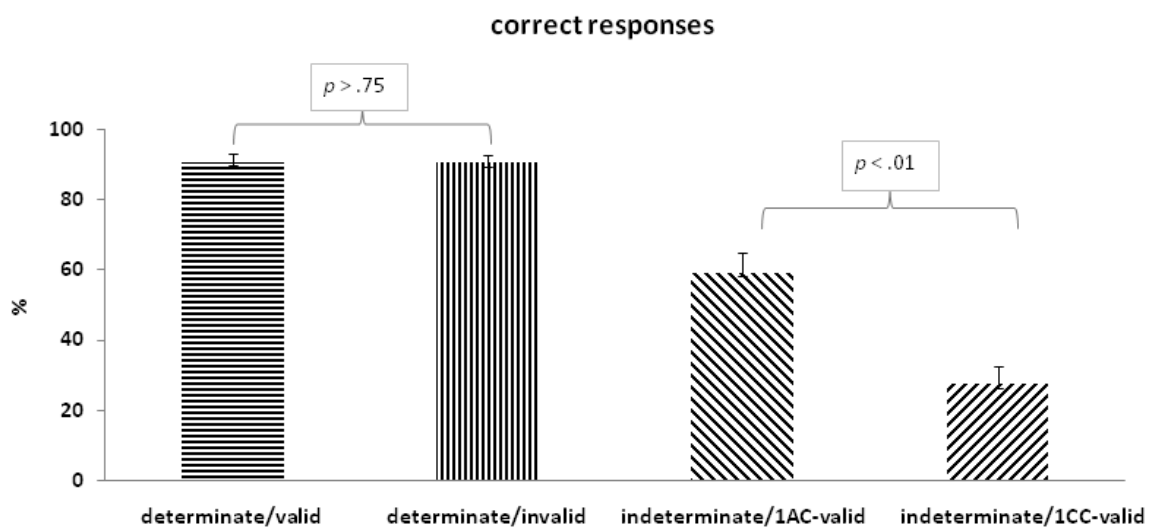


Figure 2. The left two bars show the percentage of correct responses. For the determinate problems, for half of the problems the correct response was “yes” (hit), for the other half it was “no” (correct rejection). The two bars on the right show how often the participants correctly accepted a conclusion that hold in the model built by rule 1^{AC} or rule 1^{CC} , respectively. Error bars indicate standard errors.

Conclusions that held in models constructed according to rule 1^{AC} were significantly more often correctly accepted ($M = 60%; SD = 37.40$), $t(34) = 5.49; p < .01$, than conclusions that held in models constructed according to rule 1^{CC} ($M = 27%; SD = 5.88$). This indicates that indeed the rules derived from our alternative cost functions are

more often applied than the rules derived from the classical computer science cost function. ANOVA of the decision times of correct responses also yielded a significant main effect, $F(2, 18) = 4.25, p < .05$, (see figure 3). Decision times for determinate/valid items ($M = 3.62$ s, $SD = 1.43$) were significantly lower compared to determinate/invalid items ($M = 4.89$ s, $SD = 2.69$), $t(34) = -4.67; p < .01$. Decision times for indeterminate/rule 1^{AC} items ($M = 4.16$ s, $SD = 3.07$) were significantly lower compared to indeterminate/rule 1^{CC} items ($M = 5.06$ s, $SD = 3.46$), $t(20) = 2.29; p < .05$. This implies that conclusions of the determinate/valid items were easier to confirm than the ones of the determinate/invalid items and the conclusions of the indeterminate/rule 1^{AC} items were easier to accept than the ones of the indeterminate/rule 1^{CC} items. The easier items were those where the confirmation could easily be made by following the implicit direction of the queue provided that the queue was indeed constructed from left to right.

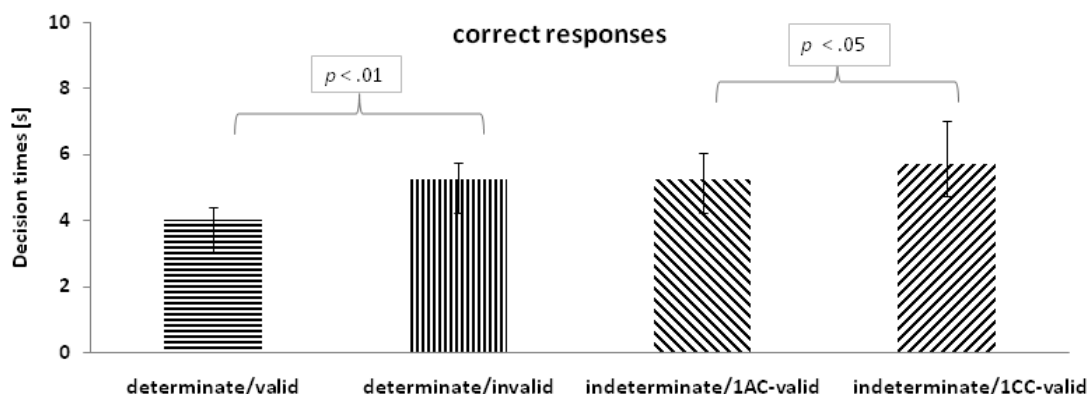


Figure 3. The two bars on the left show the mean decision times of correct responses. For determinate problems, for half of the problems the correct response was “yes” (hit), for the other half it was “no” (correct rejection). The two bars on the right show reaction times when the participants correctly accepted a conclusion that holds in the model built by rule 1^{AC} or rule 1^{CC}, respectively. Error bars indicate standard errors.

Other evidence

Further evidence for our model comes from the experiments of Jahn et al. (2007). Their participants inserted an object to an existing array, as opposed to adding it to one end of the array, more often for objects that would have been added to the left end of an array

than for entities that would have been added to the right end of an array (Jahn et al., 2007, Experiment 2, Table 4). The authors come to the conclusion that: “Given that the participants constructed arrays from left to right, they evidently found it easier to add a new entity to the right-hand end of an array than to the left-hand end of an array [...]”(Jahn et al., 2007, p. 2081).

For a queue that is constructed from left to right our model predicts this behavior: rule 1^{AC} is applied to objects inserted to the right of a reference object and therefore the objects should be inserted at the end of the queue. In contrast rule 1^{CC} would call for an insertion of an object directly behind the reference objects. Rule 2^{AC} and rule 2^{CC} are identical: if an object is to be inserted to the left of a reference object, it should be inserted directly in front of the reference object. The results of Jahn et al. (2007) confirm that reasoners construct a queue following the rules derived from the alternative cost function. This evidence combined with our findings suggests that reasoners follow the rules 1^{AC} and 2^{AC} when constructing a mental model. In particular rule 2^{AC} describes the construction process better than rule 2^{CC} if the queue is constructed from left to right, which also implies that if the description of an arrangement is indeterminate (allowing more than one model) the direction of the queue influences which model will be built.

Reasoning with the model

Once a model has been constructed it can be used to make inferences. If we build the model

apple* → mango → pear

from the premises of the first example with the implicit direction from left to right we can answer the question “Is the apple to the left of the pear?” by finding the apple in the queue and then moving further down the queue till we find the pear. This search process starts at the beginning of the queue. Since the implicit direction of the queue represents the relation in the question, once the pear is found we can answer the question with yes. That

means that the deduction process shares some of the mechanisms with the encoding process: moving through the queue and finding objects.

The deduction process uses the transitivity of the relation “to the left”. However, this does not imply that the knowledge of transitivity of the relation “to the left” is not considered until the question “Is the apple to the left of the pear?” is posed. One can argue that the knowledge of transitivity is already used in the encoding process: we only encode the information in a single model and assume that we can read out the relation between objects from the model, because we know the relation is transitive.

The question “Is the apple to the right of the pear?” can be answered in a similar way: find the apple and then move down the queue until the pear is found. However, in this case the implicit direction of the question does not represent the relation in the question. Therefore the answer to the question is No. If the objects cannot be found in the order in which they appear in the conclusion, for example “Is the pear to the left of the apple?”, there are two options: either the process has to be started again with the objects in inverse order and the inverse relation, so here we would have to test “Is the apple to the right of the pear?”. The other possibility is that we remember having found the pear, but no apple behind it, and so we search the queue again from the beginning for the apple. In both cases the queue has to be accessed twice. This illustrates we can also make predictions from the structure of the queue for the reasoning process. It should be easier to infer information that can be obtained following the implicit direction of the queue than to infer information that requires to go in the opposite direction. More specifically: if the objects in a statement are named in the same order in which they appear in the queue, it should be easier to compare this information to the queue than if they are named in the opposite order.

Empirical evidence

There is empirical evidence from an experiment we recently conducted in our lab. The experiment aims to investigate spatial belief revision. For that purpose it will be reported in detail elsewhere (Bucher et al., in preparation). Here we will report a detailed

analysis of the inference tasks participants had to conduct prior to belief revision. This analysis was done specifically for the current context as it is not of particular interest concerning the investigation of belief revision.

Material and method. Sixteen participants (three male, $M = 21.75$; $SD = 1.61$) were individually presented with 32 items, each following the same structure: two premises (presented sequentially in a self-paced manner) containing the relations “left of” and “right of” described a one-dimensional (linear) order of three (small, equal-sized, disyllabic-termed) objects, belonging to either one of two categories (tools or fruits). See Table 1 for the four possible relation orders in premises 1 and 2. Please note, as the last object always had to be inserted at the very right position of the alignment the construction of the linear order always followed a left to right direction. Participants were instructed to choose the correct order from two alternative orders presented on the left and right side of the computer monitor, indicating their choice by pressing a left or right response button with the left or right hand, accordingly. Presentation locations of correct and incorrect (mirrored orders of correct) orders were counterbalanced across the trials. Decision times as well as the number of correct decisions were recorded. Subsequently to the participant’s decision, a conclusive fact was presented. The fact was either consistent (for half of the items) or inconsistent (for the other half of the items) with the information provided by the premises and hence with the order of objects. The relation of the fact was either “left of” or “right of” (see Table 1). The Participants’ task was to judge whether the conclusive fact was consistent or inconsistent with the order of objects by pressing the respective response button (“yes” for consistent or “no” for inconsistent) with the left or right hand, accordingly. Locations of “yes” and “no” buttons were counterbalanced across participants. Thus, consistency judgments required to infer information from a linear order of three objects after construction of the order given a verbal description. The percentage of correct (consistence and inconsistent) judgments for conclusive facts with the relation “left of” and “right of”, respectively, and the corresponding decision times were recorded. Correct “inconsistent”-judgments were followed by revisions of initially constructed orders. This latter part of the experiment is not of interest here. The items were presented

in a random order to the participants. All stimuli were generated and presented using Superlab 4.0 (Cedrus Corporation, San Pedro, CA, 1999) with an RB-530 response pad running on a standard personal computer (2.80 GHz) with a 19" monitor.

Table 1
Combinations of the relations "left of" and "right of", used in the premises and facts (consistent and inconsistent) of the items

| | | Relations „left of“ and „right of“ in the premises and facts of items in experiment 2 | | |
|---|-----------------------|---|-----------------------|-----------------------|
| 1st premise | left of | left of | right of | right of |
| 2nd premise | left of | right of | left of | right of |
| Fakt (consistent or inconsistent) | left of / right of | left of / right of | left of / right of | left of / right of |

Results and discussion. Based on the information provided by the premises the correct order of objects was chosen in 97% ($SD = 3.76$) of the cases within 1.67s ($SD = 0.45$). Erroneous trials were excluded from further analyses. Separate ANOVAs for correct percentages and judgment times with the factors consistency (consistent, inconsistent) \times fact (left, right), respectively were conducted. Both ANOVAs revealed a significant interaction of consistency \times fact, correct percentages: $F(1, 15) = 10.368$; $p < .01$, judgement times: $F(1, 15) = 11.526$; $p < .01$. All main effects were non-significant ($ps > .35$). Correct percentages and judgments times for correctly judged consistent and inconsistent conclusive facts with the relation "left of" and "right of", respectively, were compared using paired t-tests. Descriptive statistics can be found in Table 2.

Table 2
Correct judgments [%] and correct judgment times [s] are shown for consistent and inconsistent facts with the relations "left of" and "right of", respectively

| | Correct judgments [%] | Correct judgment times [s] |
|-------------------|------------------------|----------------------------|
| Consistent fact | | |
| left | 98.22 ($SD = 4.88$) | 5.56 ($SD = 3.32$) |
| right | 90.18 ($SD = 11.72$) | 8.01 ($SD = 5.90$) |
| Inconsistent fact | | |
| left | 89.25 ($SD = 10.93$) | 8.69 ($SD = 3.23$) |
| right | 97.66 ($SD = 5.04$) | 6.96 ($SD = 4.42$) |

Facts in which the objects were named in the same order as in the described alignment when moving from left to right (consistent/left facts and inconsistent/right facts) led to faster decision times and a higher percentage of correct responses than facts in which objects were named in the inverse order (consistent/right facts and inconsistent/left facts).

Specifically, percentage of correct judgements of consistent/left facts ($M = 98\%$; $SD = 4.88$) were significantly higher than consistent/right facts ($M = 90.18\%$; $SD = 11.72$), $t(15) = 2.43$; $p < .05$, as well as significantly higher than inconsistent/left facts ($M = 89\%$; $SD = 10.93$) $t(15) = 3.11$; $p < .01$. Also, inconsistent/right facts resulted in significantly higher percentages of correct judgments ($M = 98\%$; $SD = 5.04$) than both consistent/right facts ($M = 90\%$; $SD = 11.72$), $t(15) = 2.16$; $p < .05$, and inconsistent/left facts ($M = 89\%$; $SD = 10.93$), $t(15) = 2.68$; $p < .05$. Differences in percentages of correct judgments between consistent/left facts and inconsistent/right facts were non-significant ($p > .75$) as well as differences in percentages of correct judgments between consistent/right facts and inconsistent/left facts ($p > .75$). Decision times were significantly lower for consistent/left facts ($M = 5.56$ s; $SD = 3.32$) than for consistent/right facts ($M = 8.01$ s; $SD = 5.90$), $t(15) = 3.11$; $p < .05$, and for inconsistent/left facts ($M = 8.69$ s; $SD = 3.23$), $t(15) = 3.71$; $p < .05$. Also the decision times for inconsistent/right facts ($M = 6.96$ s; $SD = 4.42$) were marginally significant lower than decision times for inconsistent/left facts ($M = 8.69$ s; $SD = 3.23$), $t(15) = 1.98$; $p = .066$. All other differences were non-significant (all $ps > .35$). There was a clear asymmetry concerning facts with the relation “left of” compared to the relation “right of”. For the relation “left of” the processing of consistent facts seems to be easier than for inconsistent facts while for the relation “right of” the opposite is true. The results imply that items with facts in which the order of the named objects corresponded to the left to right order of these objects in the alignment described by the premises were indeed easier to solve than items in which the objects were named in the inverse order. The results of the experiment suggest that the reactions in the reasoning task are influenced by the encoding process, more specifically by the direction of encoding. This implies that the process of encoding the information is critical for the result of the reasoning process, which qualifies this kind of reasoning as verbal reasoning. The reasoning process

described here can also explain the distance effect, where it takes less time and is more accurate to make an inference about objects that are closer together compared to objects that are further apart (Moyer & Landauer, 1967; Acuna, Sanes, & Donghue, 2002; Frank, Rudy, Levy, & O'Reilly, 2005; van Opstal, Gevers, de Moor, & Verguts, 2008). Inferences regarding objects that are further apart in the queue should take longer as more movement through the queue is required than for objects that are close together.

Computational implementation

The model construction process can be easily implemented as a computer model using the data structure linked list, consisting of nodes containing data and a pointer to the next node in the list as well as a start pointer pointing to the first node of the list (compare to figure 4). If we compare this data structure to our mental model the pointers from one node in the list to the next represent the link between the objects and the data in the nodes represent the objects. It is therefore easy to model a queue such as the one we proposed in a computer program. Algorithms in pseudo-code for moving through the list and inserting new nodes into the list can be seen in figure 4.

```

record Node {
  data    // The data being stored in the node
  next    // A reference to the next node, nil for the last node
}

firstNode // A reference to the first node of list; nil for an empty list

function InsertAfter(node, newNode) { // insert newNode after node
  newNode.next:= node.next
  node.next:= newNode
}

function InsertFirst(firstNode, newNode) { // insert node before first node
  newNode.next:= firstNode
  firstNode:= newNode
}

function Move(firstNode, X) { //move to node containing data X
  node:=firstNode
  while not node.data=X and not node.next=nil
    node:= node.next
}

```

Figure 4. Top: A pseudo-code definition of a linked list and functions to move through the list, inserting a node after a node, and inserting a node at the beginning of the list. The Node data structure consists of two fields. The variable first Node is a reference that points to the first node in the list, or is nil for an empty list. Since inserting a node at the beginning of a list requires updating first Node, it requires a separate function. Bottom: An illustration of the data type linked list.

It should be noted that technically it is not possible to insert a new node in front of a node, since we only have pointers to the following, but not to the preceding nodes. If a node is to be inserted in front of a node containing certain data, the node in front of that node is found and the new node is inserted behind it. Other than that the rules 1^{AC} and 2^{AC} can be easily implemented for the construction of a linked list. The interpretation of the direction of the links would have to be stored in an extra data structure.

Algorithmic description of the reasoning process

The reasoning process described in Section 5 can also be transcribed into an algorithm using a linked list as data structure representing the queue. Let r be a transitive binary relation and r^{-1} the inverse relation, for example r is “left of” and r^{-1} “right of”. Let

M be a model in the form of a linked list with implicit direction D of type r or r^{-1} and X and Y objects featured in that model. Given a sentence of the form XrY, the reasoning process can be described by pseudo-code algorithm in figure 5 which returns the value “true” if the sentence is true in the model and the value “false” if it is not.

```

function Search(firstNode,X,Y){    \\searches for the objects in the order XY
  node:=firstNode
  if not node.data=X then Move(node,X)
  if node.data=X then Move(node,Y)
  if node.data=X then return true else return false
}

function Reasoning(firstNode, X,r,Y){    \\tests whether the sentence is true
  if Search(firstNode,X,Y)then
    if D=r return true
    else return false
  else if Search(firstNode,Y,X)then
    if D=r return false
    else return true
}

```

Figure 5. A pseudo-code algorithm of the reasoning process using the function Move from figure. 4. The function Search tests if objects are in the list in a given order. The function Reasoning first tests if the objects are in the list in the order given in the sentence. If that is the case it checks if the implicit direction of the list (stored in D) is equal to the relation used in the sentence. If the objects are not in the list in the order given in the sentence the inverse order is checked.

The Reasoning algorithm starts with a search at the first node of the linked list. It uses the first option listed in Section 4 to verify conclusions in which the objects are not named in the same order as they appear in the queue. The other option could be implemented just as easily. An algorithm for the encoding process is not explicitly listed here. However, it can be easily constructed using rules 1^{fp} , 2^{fp} , 1^{AC} , and 2^{AC} , as well as the functions from figure 4. The very compact Reasoning algorithm demonstrates that the information is just read out of the model and no specific reasoning processes are employed. A linked list is a dynamic data structure, which means that nodes are created and discarded as they are needed. This also implies that a linked list does not exist before the first node is inserted. We believe that this property represents the dynamic character of cognition well.

Comparison with other computational models and algorithmic descriptions

There are a number of computational models and algorithmic descriptions that also address relational or spatial reasoning. Ragni, Knauff, and Nebel, for instance, introduced a computational model for spatial reasoning by mental models (SRM) which conceptualizes spatial working memory as a two-dimensional array. Within this array models can be build and manipulated using a spatial focus (Ragni et al., 2005). This theory has later been applied to the preferred mental models account (Knauff et al., 1995; Knauff, 1999; Jahn et al., 2007) to model reasoning with indeterminate descriptions in order to determine which mental models are preferably constructed by reasoners (Ragni, Fangmeier, Webber, & Knauff, 2006). While this account would also predict the results of our first experiment, it cannot account for the left–right asymmetry that we found in the second experiment. The group around Johnson-Laird provided a Lisp program called “Spatial Reasoning” which makes spatial deductions from given premises. The premises may consist of binary statements using objects and the relations right of, left of, in front of, behind, above, and below. The program tries to find a model in which all premises are true by recursively revising possible models. If it succeeds it also tries to find falsifying models to check the conclusion. Models are represented by arrays as well (Spatial Reasoning, unknown year). While the program shows that spatial reasoning can be done using models, it makes no prediction which model a human reasoner would preferably construct. Van der Henst explicitly describes how (spatial) reasoning problems can be solved through an inference rule approach. He suggests rules to solve two-dimensional spatial reasoning problems for indeterminate as well as determinate problems similar to the ones presented here, using the relations left of, right of, and in front of (van der Henst, 2002). The main aim of this work was to show that rule-based reasoning can also account for effects indeterminacy. However, the rules whose application gives an indeterminate conclusion do not reflect any preference of reasoners for a solution. So, similar to the program “Spatial Reasoning”, no predictions for preferred solutions follow from this approach. Schlieder proposes an outline for reasoning about the relative position of intervals on a

line. For some of these spatial–relational inferences there are several logically equivalent solutions, some of which are preferred by human reasoners (Knauff et al., 1995).

Assuming that these problems are solved using mental models that represent the start- and endpoints of the intervals, Schlieder provides an algorithmic description of the model construction process which is able to reproduce most of the preferences by human reasoners (Schlieder, 1999). Schlieder's model is concerned with the composition of two relations (transitive and intransitive) between three intervals (spatial or temporal) and cannot easily be generalized to other kinds of reasoning. Particularly, as the main point of interest is to explain how two relations of a different nature are connected it cannot be compared to the approach outlined here since we focus on transitive relations that can be easily combined. Also, while Schlieder's model makes predictions on preferred answers, it does not cover whether an answer is harder or easier to obtain. Bara and Bucciarelli provide a computational theory of deductive reasoning based on mental models with an implementation in the program UNICORE (UNified COmputational REasoner) (Bara & Bucciarelli, 2000; Bara, Bucciarelli, & Lombardo, 2001). Their aim is to unify the main types of deductive reasoning into a single set of basic procedures. They distinguish five phases of deduction: Construction, Integration, Conclusion, Falsification and Response. UNICORE is able to reproduce correct and erroneous performances of human reasoners of different age groups in the three areas syllogistic, propositional and relational reasoning. For relational reasoning Bara, Bucciarelli and Lombardo examine determinate three term series problems. They assume that models are ordered left to right according to the sequential order in which the state of affairs they represent are described in the sentence. In accordance with the mental model theory they claim that two models are created, one from each premise, which are then combined into a single model to make an inference (Bara et al., 2001). While this is not stated explicitly, their approach implies that inferences whose relations correspond to the left to right ordering in their models should be drawn faster than other inferences. However, since they assume that all models are constructed in the order in which objects are named in sentences, independent of the relation used, they would use models constructed from left to right for one half the items

and models constructed from right to left for the other half of the items of the experiment reported in Section 4. This would lead to the prediction that on average there should be no difference in reasoning time for conclusions using relation left and conclusions using relation right, which does not match the results we found. For indeterminate problems the theory does not make predictions for preferences of reasoners. A completely different approach uses the LISA model of analogical reasoning by Hummel and Holyak. This connectionist model employs a neural network to model reasoning. Objects of propositions as well as their relations are represented as patterns of activation distributed over semantic units, which are integrated into representations of propositional structures using synchrony of firing. Through its structure LISA can account for the limits of working memory (Hummel & Holyoak, 2003, 2005). However, LISA focuses on analogical reasoning that is finding correspondences between elements that play parallel roles in two similar situations. While this is an important part of relational thinking, we do not believe that the kind of problems discussed in this work are solved by analogical reasoning. Therefore, there is no straight-forward way how our kind of indeterminate problems can be solved in LISA.

Discussion

We introduced an approach about how relational reasoning can be modeled as verbal reasoning. The main idea is that the deduction process does not necessarily require deduction-specific mechanisms to operate on internal representations. Instead we assume that a simple order of objects (represented by words) and some genuine verbal cognitive mechanisms might guide the reasoning process. Following Polk and Newell (1995) we assumed that the cognitive processes in deductive reasoning can be based upon the same processes as language comprehension and generation. Our model satisfies the criteria of verbal reasoning as outlined by Polk and Newell (1995). Verbal in that sense refers to transforming between verbal and semantic representations, that is constructing the queue (encoding) and “reading out” information that is not explicitly provided by verbal descriptions. The most important point is that “reading out” information from the queue

does not require mechanisms that are especially dedicated to deduction. Rather, reasoning is accomplished by applying more well-trained linguistic processes that are more likely to be applied by individuals not trained in logic. The approach does not obviate specific mechanisms but provides a more parsimonious explanation how inferences can be drawn from given information without assuming additional mechanisms. Mechanisms operating on mental models and not reasoning-specific mechanisms are applied during “reading out” information from the queue. The claim is that individuals – especially when untrained in logic – are more likely to apply well-trained linguistic-based, rather than deduction-specific mechanisms to derive implicit information from given information. The algorithms outlined in Section 5 demonstrate how these reasoning processes can be realized by very simple means. Our empirical work has shown that the approach and the related cost measure leads to good predictions about what kind of model will be created. It predicts behavior better than the standardized computational complexity approach. In addition predictions from the suggested reasoning process were empirically supported.

While the present experiments only used problems with two premises, we believe that the postulated rules also apply for more than two premises and three objects, as long as the premises all contain transitive relations describing the same dimension. It is also possible to mix relations of the same dimension such as left and right, as done in our second experiment and in many other experiments (e.g., Ragni et al., 2006; Jahn et al., 2007). Also the mechanisms described by us are not limited to spatial relation, but are general enough so that they can be employed for all transitive relations. However, although in principle the suggested mechanisms might operate with non-spatial transitive relations in the same way as with spatial relations, the influence of aspects that result from content-inherent factors (e.g., complexity modulating aspects such as lexical marking of adjectives or congruence of relations in the premises and conclusions; Clark, 1969) on the processes have to be investigated and specified.

We provide algorithms for the construction and reasoning process, making it easy to implement the model. The proposed computational implementation is more frugal concerning data-structure and algorithms compared to alternative approaches listed in

Section 5 while still containing all aspects of reasoning about linear orders outlined in this study. Also, this is the first model that can account for a left–right asymmetry as found in our second experiment or reported by Jahn et al. (2007).

However, some issues concerning the model still have to be specified. A question that remains is whether the starting point of a queue is really a link like all the other links in the queue. Since this link is different concerning its cognitive nature it might be weaker or stronger than the links between objects in the queue. If this is the case, it would make it either easier or harder to insert an object at the beginning of the queue than between two objects of the queue.

Another point is that if, for some reason, we already know that a reference object is in the queue, and we have to insert an object in front of it, it is more cost efficient to insert a new object at the beginning of the queue instead of first finding the reference object in the queue to insert the object directly in front of it. In this case inserting the object at the beginning of the queue saves moving through the queue. The same is not true for inserting an object behind a reference object. Here we always have to move through the queue, at least to the reference object.

A third problem is that we postulate that the implicit direction of a queue can theoretically be chosen freely, with the choice in our spatial reasoning tasks strongly being influenced by cultural and linguistic factors, as discussed in Section 2. Can this choice be further influenced? In spoken language emphasis can be used. For instance in the sentence: “The apple is to the left of the mango” intonation can be used to put the focus on the mango. This might prompt reasoners to change their preferred direction of construction. In addition, to evaluate the influence of culture comparison between participants from a left-to-right reading country with those of a right-to-left reading one would be interesting.

Finally, the validity of the alternative cost measure should be examined in more detail. One problem of our approach results from the assumption that it is easier to move through the queue than to alter existing links, no matter how far we have to move. However, it is possible that, if the queue becomes larger, there might exist a critical

distance after which more mental effort is required moving this distance through the queue than altering a link. This would imply that if the queue reaches a certain number of objects new objects would not necessarily be attached to the end of the queue any more. If this is the case one could identify a “break-even-point” and specify how many objects one has to move through the queue to induce the same cognitive effort as creating a link.

We consider our approach to be a helpful addition to the long lasting controversy between models and rules in reasoning (e.g., Hagert, 1984; Johnson-Laird, Byrne, & Schaeken, 1994; Rips, 1994). In fact, models are often identified with visuo-spatial processing and rules with linguistic or sentential mechanisms (e.g., Goel, Buchel, Frith, & Dolan, 2000). Our study, however, shows that this distinction does not reflect the actual differences between the two approaches. In fact, our approach is a model-based approach, because at no time during the inference process rules of inference are used and the new information must be derived from the queue – the model. On the other hand, our results suggest that such models can be the basis of verbal reasoning, and visuo-spatial processes are not necessarily involved in the inference.

Overall, we were able to present some evidence for our assumption that the process of constructing a verbal mental model from premises influences deductive relational reasoning. For indeterminate problems, we can predict which model is preferred over others. For determined problems, we can make predictions on how the conclusion should be phrased so that it can be easily confirmed or invalidated. While our model cannot necessarily be generalized to other domains of reasoning we feel that it can describe some aspects of human reasoning with transitive relations and that it demonstrates that relational reasoning can also be conceived of as verbal reasoning.

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Part 6

Conclusion

Conclusion

Humans have to process an unbelievable amount of information in everyday life and sometimes things appear to differ than hitherto assumed. The first impression of a situation has to be adjusted in the light of additional information or maybe an incontrovertible fact contradicts with parts of what is believed to be true. In such cases an existing belief needs to be revised in order to regain consistency between what is believed and what is irrefutably caused by the world. In general these cognitive processes are referred to as "belief revision", and some experimental work has been done mainly in reasoning with conditional statements ("if...., then...") (Elio & Pelletier, 1997; Johnson-Laird, Girotto, & Legrenzi, 2004a). Belief revision is effected by many different factors like general laws, or the type of information (e.g. conditional and categorical premises, or reliable and unreliable information sources) (Revlis, Lipkin, & Hayes, 1971; Dieussaert, Schaeken, De Neys, & d'Ydewalle, 2000; Girotto, Johnson-Laird, Legrenzi, & Sonino, 2000; Revlin, Cate, & Rouss, 2001; Politzer & Carles, 2001; Wolf, Rieger, & Knauff, 2012), as well as difficulties to reconsider prior beliefs (Knauff, Budeck, Wolf, & Hamburger, 2010).

However, due to the fact that cognitive processes underlying belief revision in the spatial context were unexplored up to now, the intention of the present thesis was to investigate human belief revision in the area of relational reasoning. Given that relational inferences are frequently used in our daily life (Goodwin & Johnson-Laird, 2005; Knauff, 2013) and relations are intimately linked to space (Gattis, 2001; Knauff, 1999) it is reasonable to take a wider view of the present findings.

Generally speaking, two main questions were of interest over the course of experiments: How do humans construct spatial beliefs and how do they revise their beliefs if new pieces of information contradict earlier assumptions? There is evidence that reasoners order objects spatially even when the relations are non-spatial and 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). However, how we infer new information about relations between objects is the subject of

theories about relational reasoning (Goodwin & Johnson-Laird, 2005) and there are several theories which try to explain the underlying cognitive processes. For instance syntax-based theories suggest that reasoning processes are based on operations similar to the syntactic rules of formal logic (Hagert, 1984; Rips, 1994; Braine & O'Brien, 1998), but they have serious difficulties to explain inferences with spatial relations (overviews in Goodwin & Johnson-Laird, 2005; Knauff, 2009, 2013).

Given the vast empirical evidence that people use the linguistic description of a situation for constructing an integrated representation by translating such given information into a mental model, whereas these integrated representations constitute models in the strict logical sense and represent in "small scale" how "reality" could be (Craik, 1943), it was reasonably assumed that spatial reasoning most likely relies on spatial representations which reasoners construct in some cognitive space. This is best accounted for by the mental model theory (MMT) which postulates that reasoners use the meaning of assertions and general knowledge to construct single models of possibilities compatible with these assertions. Such a single set of models build the basis for subsequent reasoning processes (Johnson-Laird & Byrne, 1991; Polk & Newell, 1995; Goodwin & Johnson-Laird, 2005) and is in this sense essential for spatial belief revision.

For this reason the theoretical framework of the mental model theory (e.g. Johnson-Laird & Byrne, 1991; Knauff, Rauh, & Schlieder 1995; Vandierendonck & de Vooght, 1997; Knauff, Rauh, Schlieder, & Strube, 1998; Schaeken, Girotto, & Johnson-Laird, 1998; Ragni, Knauff, & Nebel, 2005; Rauh, Hagen, Kuss, Knauff, Schlieder, & Strube, 2005) build the basis for the presented cognitive research of spatial belief revision.

Knauff et al. (1998) have specified three distinct phases for the special case of spatial reasoning and they became of crucial importance for understanding cognitive processes underlying spatial belief revision. For spatial belief revision three main assumptions were worked out which are closely related to reasoning phases suggested by Knauff and colleagues (1998).

(1) Spatial belief revision relies on the construction and inspection of spatial mental model

It is assumed that a reasoner passes through differentiable stages during reasoning processes. Insofar as it can be assumed that spatial belief revision can be deemed as a distinct phase, it is reasonable that previous stages (e.g. construction and inspection) are inevitably performed. Knauff et al. (1998) suggest a construction phase, during that reasoners construct a mental model, reflecting the information of the premises, an inspection phase, during which the model is inspected for implicit information of the premises, and a variation phase, during which alternative models are constructed and investigated concerning their compatibility with the information given by the premises. If necessary the third phase results into falsification of the preliminary mental model, constructed during the first phase. This procedure assumes that when the construction of a mental model compatible with given information is accomplished, the model as an entity is stored in memory. This is supported by previous studies, which have shown that the gist of determinate descriptions can be better remembered than the verbatim information compared to indeterminate descriptions (Mani & Johnson-Laird, 1982).

As a consequence spatial belief revision follows a construction and subsequent inspection of a spatial mental model (implicating inconsistency detection as a prerequisite for a subsequent belief revision)

Construction of spatial mental models

Some of the present studies make an attempt to describe cognitive processes underlying the construction of spatial mental models on the basis of experimental investigations and computational implementations. Generally, it can be concluded that humans have some preferences when constructing spatial mental models from premises. Results presented in this thesis add to the body of evidence that these cognitive processes are influenced by various factors.

Working direction. It seems that relations are integrated either into a vertical or horizontal linear order (De Soto, London, & Handel, 1965; Huttenlocher, 1968) and that

the left end of this linear spatial representation is the preferring starting point resulting in a working direction from left to right reflecting the cultural bias to work in the same direction as reading and writing (Chan & Bergen, 2005; Spalek & Hammad, 2005). Results from the first study (*Chapter 1: The construction of spatial mental models- a new view on the continuity effect*) demonstrate that humans construct spatial mental models preferably in this left to right manner. In this context it is essential that the direction in which new objects can be integrated into an existing model modulates the complexity of construction processes, as well as the number of objects that have to be relocated within a mental model (see also *Chapter 4: Relocating multiple objects during belief revision*).

The working direction also affects the way how humans make conclusions. In the last study (*Chapter 11: A model for relational reasoning as verbal reasoning*) presented in the thesis results suggest an asymmetry between facts relations. While participants needed less time to process consistent relational statements with the relation “left of”, the inverse was the case for inconsistent statements. Both statements imply an order objects corresponding to the left to right order described by the premises. For the arrangement A – B – C the consistent fact “A left of C” displays the same order of the objects A and C like “A right of C”. It seems that the reasoning process is facilitated by the direction of encoding from left to right.

Order effects. For the construction of spatial mental models results suggest an order effect in the sense that the construction processes followed the order of objects as they were mentioned in the relevant spatial description. For example, when participants were confronted with a spatial description like “The red block is to the left of the blue block” and “The red block is to the right of the blue block” the red block was inserted first and then the blue block was placed accordingly (*Chapter 2: Cognitive processes underlying spatial belief revision*). This finding was also robust even when native speakers of Russian performed the task (*Chapter 9: Spatial reasoning in native speakers of Russian and German*). Please note that our results refer just to processes of processing the first premise.

Principle of parsimony. A detailed computational model of “*preferred inferences in reasoning with spatial mental models*” (PRISM; Ragni & Knauff, 2013) is mainly based on assumptions that are supported by findings from the present thesis. In general it is assumed that a reasoner strives to integrate all tokens into a model as soon as possible. This is even the case when given information is not related to each other. This procedure might be accounted for by characteristics of the working memory. Information provided by the premises has to be held for processing and manipulation in a compressed format, given the limitation of the working memory capacity. Humans seem to merge unrelated information into a preliminary mental model in order to have more cognitive resources available for premise processing, with the consequence that subsequent additional processes are needed to modify this preliminary mental model.

A second essential assumption is that humans try to avoid relocating objects that are already represented in the model. This implies that if a new object has to be inserted into an existing model, the first free position that fulfils all information from the premises is used to insert the object following principles like the preferred working direction (*Chapter 11: A model for relational reasoning as verbal reasoning*). In exactly the same manner a preliminary mental model is constructed on the basis of unrelated spatial information, which is then modified if necessary as the description continues.

For preliminary mental models the suggestions of a fast, straightforward and ongoing information integration seem to be more relevant than the avoidance of object relocation. A reasoner seems not to prefer an alternative strategy, since it is more parsimonious to keep premise information in a preliminary mental model with an annotation of a temporary link than to hold the verbatim information or multiple models in mind. This finding fits well with the principle of parsimony and with previous findings suggesting that humans prefer to construct as few mental models as possible (Knauff et al., 1995; Rauh, Schlieder, & Knauff, 1997; Ragni et al., 2005; Rauh et al., 2005; Ragni, Fangmeier, Webber, & Knauff, 2006; Ragni & Knauff, 2013) and offers at the same time a new view on underlying construction processes and the understanding of cognitive parsimonious principles.

Links between tokens. Another account that explains how we deal with relational problems relies on the linguistic structure of the premises and proposes that reasoning is accomplished mainly by certain general linguistic processes, identical to the process of comprehension. This would correspond to a linguistic representation that contains the underlying meaning of the premises (Polk & Newell, 1995; Clark, 1969). In the last part of the experimental section a study was presented that builds a bridge between relational reasoning and verbal reasoning (*Chapter 11: A model for relational reasoning as verbal reasoning*). We introduced an approach about how relational reasoning can be modeled as verbal reasoning. The main idea is that the deduction process does not necessarily require deduction-specific mechanisms to operate on internal representations. However, the approach is a model-based approach, because at no time during the inference process rules of inference are used and the new information has to be derived from the queue – the model.

More interesting at this point is the assumption that tokens within a mental model are connected by a link. A question that remained was whether the starting point of a model is a link, like all the links between tokens. Since this link is weaker or stronger, it would make it either easier or harder to insert an object at the beginning of the model than between two objects of the model. Experimental findings from the first study (*Chapter 1: The construction of spatial mental models- a new view on the continuity effect*) might answers some of these questions, although it is not possible to answer all of them.

For example, in the first experiment and the semi-continuous condition participants had to insert the last introduced object directly to the leftmost side of an existing model and thus to create a link between two objects, and to define a new starting point. Participants needed more time than in the continuous condition when the new object has to be linked to the end of an existing model. Longer processing times in the semi-continuous condition should be required for switching in another working direction (from right to left as opposite to a straightforward insertion to the right), longer distances between the two related objects and defining a new starting point. However, in the second experiment in which a working direction from right to left was suggested processing times did not differ

between both conditions. In this sense it seems that other factors than the strength or weakness of a starting points' annotation determine the cognitive effort needed to insert a new object at a beginning or end of an existing model.

It seems that relations between objects that are determined by given premises are even the strongest. New partial models which are constructed on the basis of unrelated information are connected by a temporary link that is not as strong as the connections between the actually directly related objects within a preliminary model. In cases where additional information confirms the preliminary arrangement, this link is translated into a connection that resembles an already existing link. On the other hand cognitive effort is needed to disconnect a partial model, to relocate it to a new position and to create a new link in cases when new information suggests a rearrangement of the preliminary model. However, in cases when premise information are incorporated into one unified mental model, reasoners are able use this mental model for further reasoning processes.

Inspection of spatial mental models and inconsistency detection

Quite often new information run counter previously provided information and inferences allow the detection of inconsistencies with conflicting information (Johnson-Laird et al., 2004a; Johnson-Laird, Lergenzi, & Girotto, 2004b). In all spatial belief revision experiments presented in the thesis participants had to detect inconsistencies between an initially constructed model and an incontrovertible fact. In some cases they do not have to make this decision explicit, whereas in other cases they were explicitly asked to decide whether the conclusive fact was consistent or inconsistent with the order of objects. The very well performances over all experiments lead to the assumption that humans are quite good in detecting inconsistencies. The inconsistency detection seems to be based on a scanning process of the initially constructed mental model (e.g. Ragni et al., 2005).

In the fMRI study inconsistency detection and revision processes are not distinctly divided but neuronal activity gives a clue for a better understanding of underlying cognitive processes. Activations in the dorsolateral superior frontal gyrus and the inferior parietal lobe (supramarginal and angular gyri) lead to the assumption that inconsistency

detection processes are based on mental models. Executive components and working memory capabilities are taken into account and are typical for deriving conclusions in deductive reasoning (Kübler, Dixon, & Garavan, 2006; Reverberi et al., 2007; Knauff, 2009). Since the superior frontal gyrus is associated with monitoring and manipulation of mentally represented information (Du Boisgueheneuc et al., 2006) it seems to be essential for an inspection of an initially constructed mental model in order to compare premise information represented by a mental model, and the indisputable fact. To pave the way for subsequent revision processes the insula seems to play a crucial role by forwarding essential information from the inconsistency detection phase, since the insula seems to be involved in attentional switching processes and working memory capacities management, as well as in preparing a rapid access to the motor system (Menon & Uddin, 2010). As said above, the cognitive processes of inconsistency detection and spatial belief revision were not explicitly divided and thus the present is based on speculations. Further investigations are needed to work out more precisely neuronal correlates of both processes. For instance, it is now possible to adapt the measurement in the scanner by defining regions of interest in advance or to add additionally to revision tasks a condition in which participants just have to check a statement for inconsistency.

(2) The revision process relies on a variation of an initially constructed spatial model.

Whereas in other domains belief revision is accompanied by a rejection of certain premises, in the spatial context spatial belief revision is assumed to be accomplished by a variation of initially constructed spatial mental models. But what does that mean in practice? Generally speaking humans have to decide which parts of all given information at a moment to retain and which one to discard, if not all information can be true. It is certain that the indisputable fact has to be taken into account and should be incorporated into an existing model. However, there are several, frequently logically equivalent alternatives how to vary initially constructed models in order to reestablish consistency within belief sets. All experiments in the present thesis conducted to investigate spatial

belief revision show that logic does not help reasoners with their decision which alternative to prefer. In a similar vein humans do not prefer to retain or to reject one premise over the other, but rather the variation itself is assumed to be guided by fact's information while conserving as much of the initial information as possible. Closely related to assumptions worked out by the mental model theory, the revision process is supposed to rely on local transformations within mental models in which tokens are moved to new positions. In this sense we investigated what processes guide belief revision in reasoning with spatial mental models.

According to first investigations of underlying cognitive processes of spatial belief revision the question was whether revision processes of initial models are guided by vital steps remembered from the construction phase or whether they solely rely on spatial information provided by inconsistent facts. Whereas the construction process seems to be influenced by the order in which objects are mentioned in a spatial description, in the sense that the first mentioned object was also focused first, this order effect did not occur during variation. This finding implies that different principles are used during the construction and the variation phase, respectively, suggesting distinct underlying cognitive mechanisms, accordingly. However, together with the assumption that the starting point for an inspection of an initially constructed mental model is the last inserted object, it was assumed that this object could be preferably relocated (Knauff et al., 1998; Ragni et al., 2005).

But results show deviate from these expectations and assumptions that for spatial belief revision it is not essential which object has been inserted last into a mental model (for overviews see Chapter 2 and 9). In this sense, variation processes are not influenced by information used during the construction phase. Furthermore, these findings support the assumption that humans revise spatial beliefs on the basis of previously constructed and mentally stored models. The inconsistency detection is deemed to be a prerequisite for subsequent belief revision performances. This procedure can be described as a kind of mental scanning of tokens that are mentally related to each other in the way that all explicit and implicit given objects and relations are represented.

This is in accordance with the notion that manipulating mental models is more parsimonious than storing initial descriptions and vital steps that are used to construct these models. Furthermore, studies presented in this thesis show that determinants of preferences for variations of simple one-dimensional horizontal arrangements of three objects, are semantic cues of contra factual information. Verbally provided statements guide variations and lead preferably to variations based on the relocation of to be located objects (LOs) relative to reference objects (ROs) (see also point three in this section).

The variation principle guided by semantic cues applies as long as the complexity/demand of a task does not increase. The complexity of a task might increase with the number of items, chunks, or units of information that are involved in this task (Miller, 1956). Relational complexity results from interactions of components such as the number of objects, relations, and the type of relation (Halford, Wilson, & Phillips, 1998; Phillips & Niki, 2002). Assuming that humans are limited in their cognitive resources, complexity draws on processing capacity – that is, the more complex a problem is, the more cognitive resources are required to solve it. In this sense results from the study presented in the third Chapter (*Construction and Revision of Spatial Mental Models under High Task Demand*) show that humans respond to a complex task in the spatial belief revision context by the use of a different strategy than the LO-principle.

The study shows that under certain circumstances humans fall back on principles and strategies used during previously performed cognitive processes (e.g. construction processes) to perform a subsequent belief revision. Based on findings from the first study (*Chapter 1: The construction of spatial mental models- a new view on the continuity effect*) the question was whether increased difficulty of the construction process affects revision. More precisely, it was shown that constructing a mental model on the basis of discontinuously presented information requires mental operations, similar to a mental relocation performed during spatial belief revision and the question was whether relocations already performed during the construction phase were repeated for revisions when demands are high.

Whereas reasoners are more likely to use the LO-principle when more cognitive resources are available, they tend to use one and the same strategy for constructing and revising a mental model under high task demand. Summarizing the above, it can be said that for subsequent variations of spatial mental models it is essential under which circumstances a mental model has been constructed. Subsequent revision processes are modulated and influenced by construction processes using the episodic trace recorded during construction. This principle is used to accomplish the revision, only in cases where the construction requires switching between different construction strategies (in this case between construction processes on the basis of continuously, semi-continuously or discontinuously provided information).

Nevertheless, it is not clear at this point in which way the variation processes are indeed affected. Are variation processes with a previously performed complex construction task impeded in the sense that less cognitive resources are available and thus a just performed strategy is used? Or are these findings in line with principles of parsimony by repeating a just performed cognitive strategy that resembles variation processes used for spatial belief revision? To answer this question it is necessary to present high demand construction tasks that do not imply revision-like processes during the construction phase in combination with subsequent revision performances. By doing so it might be possible to answer the question whether humans act cognitively economical and use previously performed processes for spatial belief revision, only if they are similar to variation processes of spatial belief revision.

However, please note that the reason for another variation strategy at this point seems not to be an increasing number of objects or anything like it, in the sense that relational load is deemed not to be ascribable to item load per se (Halford et al., 1998; Phillips & Niki, 2002). For instance, in Chapter 4 (*Relocating multiple objects during belief revision*) the question was investigated whether the number of objects involved in model variation processes might influence revision processes. It was assumed that from an economical point of view, changes based on model variations should be kept as minimal as possible. In the course of spatial belief revision it was possible to relocate one or two

objects in order to regain consistencies. Again results show preferences for variations that were based on the relocations of LOs relative to ROs, but the variation that involved two, compared to one object, demanding higher cognitive resources what was reflected by longer decision times.

In this case it seems to be cognitively more economical to relocate two objects within a mental model in the sense of the principle of minimal changes (Harman, 1986) which says that reasoners try to keep as much as possible of a model unchanged and only vary what is absolutely necessary in order to gain a consistent mental representation of the problem scenario. These findings are also in line with findings from the first study presented in this thesis (*Chapter 1: The construction of spatial mental models- a new view on the continuity effect*). It seems that in all cases where it is possible to retain initially processed premise information that is mentally represented by links between two tokens, humans tend to do so. Even if this implies that two objects have to be relocated within a mental model and as a consequence thereof humans need more time in to relocate two objects within a mental model than for the relocation of a single object.

Another interesting corollary is that humans seem to simulate the mental variation which is performed during spatial belief revision. The fourth part of the thesis was concerned with the question whether spatial belief revision can be indeed described as a mental relocation of tokens within a mental model. To test this, assumptions from the grounded cognition approach and mental models theory were combined. Whereas the mental models theory assumes that humans reason by the use of mental simulations, and infer from simulations what might be the case in a certain situation the results additionally underpin the assumption that also mentally performed relocations are simulated and take knowledge about physical objects properties during spatial belief revision into account. More precisely, for the variation of mental models it matters what kind of objects are incorporated in this mental model. Different object properties are not considered in the same manner for spatial belief revision. The size and the movability of objects matters, when we think about relocating objects mentally. Small objects are preferably relocated to big objects and easier to move objects are faster relocated than more difficult to move

objects. Those findings are in line with the idea of grounded cognition and tie in with results of studies that suggest that we exploit mental simulation for reasoning.

For the case of spatial belief revision this means that the mental motion of an object from one place to another place within a mental model takes into account the objects bulkiness or inertia, which is reflected in preferences and relocation times. Findings from the fMRI study underpin the assumption that the revision processes is a local transformation of mentally represented objects. Activations in a parieto-fronto-central network are associated with action-related language processing and grounded cognition (Hauk, Johnsrude, & Pulvermüller, 2004; Pulvermüller, 2005; Tettamanti et al., 2005; Boulenger, Hauk, & Pulvermüller, 2009; Raposo, Moss, Stamatakis, & Tyler, 2009; Esopenko et al., 2012) and are also found to be involved in the presented fMRI study during spatial belief revision. The revision seems to be based on mentally represented objects that are most likely processed and integrated by taking visuo-spatial brain regions into account.

(3) Spatial belief revision is sensitive to a functional asymmetry between two arguments (located object – LO and reference object – RO) of a binary spatial relation

As mentioned before all spatial belief revision experiments presented in this thesis, with exception of the fMRI study, offer multiple logically equivalent solutions for revision. Thus, in the revision tasks reasoners had to solve this ambiguity. Following the preferred mental model account for indeterminate descriptions (Knauff et al., 1995; Knauff, 1999; Ragni, et al., 2006; Jahn, Knauff, & Johnson-Laird, 2007), it was assumed that humans would also show certain preferences for spatial belief revision processes. As already discussed, findings on spatial belief revision suggest that reasoners vary spatial mental models. In this context they show clear preferences for certain variations over others. Over all experiments spatial belief revision processes seem to be sensitive to an asymmetry between the RO and LO of a binary relation. This phenomenon is well known from many studies in the area of spatial cognition research (Talmy, 1983; Herskovits, 1986; Hayward

& Tarr, 1995; Jackendoff & Landau, 1995). When processing spatial descriptions the LO is considered to be the more flexible element and it is easier to move this object mentally to another position within a model than the RO, which is viewed as a stationary “landmark” and should be left at its initial position (e.g., Herskovits, 1986; Hayward & Tarr, 1995). moreover, it is important to note that in general the sentence structure determines which object is flexible and which one is perceived as more stationary. It seems that humans use some objects more likely as an LO in a sentence than other objects and additionally, that this preference is based on physical object properties such as size. This distinction is closely related to the intention of our communication. For instance, to describe a bicycle’s position you would not phrase the sentence "the church is behind the bicycle", but "the bicycle is in front of the church" (Landau & Jackendoff, 1993). Describing the church’s position we would most likely select another large or at least another stationary object as the reference object. For this reason it is possible to claim out that in spatial descriptions untypical LOs (e.g. small objects to describe the position of a large object) and vice versa typical ROs (e.g. large objects to describe the position of a small object) exist.

Based on this the very first experiments conducted in the field of spatial belief revision have used simple spatial models of “neutral” 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). By doing so it was possible to work out basic cognitive principles which in general guide spatial belief revision, a principle which we refer to as the LO-preference. No matter if a spatial belief revision according to the LO-preference implies a relocation of more than one objects, or relocation to a non-preferred working direction from right to left, in almost 90% of the cases the LO of an inconsistent fact was relocated within a model in order to regain consistency. Furthermore, participants completely ignore the logical equivalent solution of an RO-relocation. All studies show that the LO-principle can be deemed as a strong cognitive principle for spatial belief revision processes. This preference was even

shown in cross-cultural study with native speakers of Russian (*Chapter 9: Spatial reasoning in native speakers of Russian and German*).

In the course of experiments, the question whether this strong preference is modulate-able became important. Among other factors we manipulated the number of items, premise orders, object properties, or even the plausibility of arrangements. However, some of the conducted studies give reason to assume that this preference is under some circumstance modulate-able for instance during reasoning about objects with specific properties (*Chapter 6: Grounded Spatial Belief Revision*). In Chapter 8 (*Plausibility and visualizability in relational belief revision*) a study was presented that tested whether reasoners hold on to the LO-preference, even when it leads to implausible models; implausible in the sense that the revised arrangement does not take the order of properties and relations into account. The basic assumption was that reasoners order objects spatially even when the relations are non-spatial. For example, “Venus shines brighter than the moon but the sun shines even brighter”, can easily be reflected by the order: Moon – Venus – Sun (e.g. Knauff, 1999). For this description the arrangement Sun – Venus – Moon could be deemed as implausible, assuming that humans tend to construct spatial mental models in a preferred working direction from left to right (*Chapter 1: The construction of spatial mental models- a new view on the continuity effect; Chapter 11: A model for relational reasoning as verbal reasoning*).

Findings from this study revealed two main things; the LO-preference remained the guiding revision principle even when the resulting model was implausible and 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, whereas relations that were rated as easy to represent spatially were manipulated faster during the revision phase. Particularly with regard to findings from the study presented in Chapter 6 (*Grounded Spatial Belief Revision*) one might assume that the plausibility of spatial arrangements should stronger affect spatial belief revision processes in the sense that knowledge of object properties and their relations to each other have been taken into account during spatial belief revision. But what do these divergent findings mean for

theoretical assumptions formulated for spatial belief revision? Is spatial belief revision affected by prior knowledge or is it solely a variation process of initially constructed mental models that takes the asymmetry between two arguments of an inconsistent fact into account?

However, on closer inspection problems presented in both studies differ in some crucial points. Some of them are discussed in the following for the attempt to answer these questions. One crucial point is that participants were forced in the plausibility study to partially “ignore” plausibility of relations in order to construct the correct initial model from plausible and implausible statements during the construction phase. Assuming that humans are able to adapt cognitive strategies even by performing mentally spatial belief revisions this might have triggered them to do the same in the revision process. This could be the reason why they also ignored the plausibility of the revised model and followed just the LO-principle. If interpreted correctly, this would imply that construction and revision are ongoing processes that are not as distinct as previously assumed (*Chapter 2: Cognitive processes underlying spatial belief revision; Chapter 3: Spatial belief revision; Chapter 4: Relocating multiple objects during belief revision*). This assumption is supported by findings from the study presented in Chapter 5 (*Construction and Revision of Spatial Mental Models under High Task Demand*), showing that humans repeat under high task demand cognitive processes from construction during spatial belief revision. It is reasonable to conclude that the transition between construction and revision processes will be smoothed in cases when either this procedure leads into less cognitive effort and suggests an economical strategy or the task is demanding highly cognitive resources and to avoid switching between strategies for both processes is the only way to solve the task.

However, another interesting point is that the grounded cognition study (*Chapter 6 Grounded Spatial Belief Revision*) refers explicitly to prior knowledge regarding object properties, whereas the plausibility study (*Chapter 8: Plausibility and visualizability in relational belief revision*) is concerned with different types of relations between objects and takes object properties in an implicit way into account. That different types of relations are considered during spatial belief revision is supported by the finding that the

visualizability of a relation can modulate spatial belief revision performance. In line with findings that relations which are easy to visualize as mental images impede reasoning (e.g. Knauff & Johnson-Laird, 2002) longer revision times corroborate these assumptions.

Based on neuro-imaging studies Knauff (2009) suggests the temporo-occipital network to be involved in premise processing in a way that a visual mental image is formed on the basis of given information, and that general knowledge about the specific situation and the entities is taken into account. The temporo-occipital network is one of some networks that have been found activated during spatial belief revision (*Chapter 7: Neuronal correlates of spatial belief revision*). Bringing together behavioral data and neuronal activation it is reasonable to assume that spatial belief revision is also based on prior knowledge humans have about objects and relations. To sum up, humans tend to use the more economical strategy to reach a goal and based on the strong preference of the LO-principle that has been in the proper meaning of the word reduced in just one study (*Chapter 5: Construction and Revision of Spatial Mental Models under High Task Demand*) it seems that this revision strategy is the most parsimonious one as long as the construction process does not require more cognitive resources or prior knowledge about objects and relations do not offer another way of proceeding. The more demanding a task, the more it is necessary to be economical with cognitive resources. Economic processing is, certainly among other economic procedures, achieved by avoiding strategy switches during a problem-solving procedure and reasoners might stick to a strategy that had been applied successfully previously in the process. There is evidence that humans are also sensitive to the LO-RO asymmetry during construction processes (Oberauer & Wilhelm, 2000) and in this sense it is not surprising that humans also apply this strategy for subsequent cognitive processes that can be deemed as a continuation if previously performed reasoning processes.

The present thesis makes an attempt to investigate underlying cognitive processes of construction and revision of spatial mental models. Results suggest some important and crucial points and offer a new view and a better understanding of human reasoning capabilities. Reasoning about spatial relations encompasses multiple reasoning abilities

and findings suggest that humans tend to use parsimonious and economical strategies for both construction and revision processes. There is evidence that humans more generally prefer to integrate new entities into an existing mental model rather than to construct multiple models, and it does not matter whether the mental model is a “regular” or a preliminary one. It seems to be a more practicable strategy to incorporate not related information into one preliminary mental model and to process subsequently a revision-like process in order to regain consistencies between all given information, than to hold premise information separately in mind. In a similar vein, humans perform subsequent cognitive processes of belief revision on the basis of previously constructed mental models that are manipulated as less as possible.

The first aim of spatial belief revision is to regain consistency and the process follows the minimal change principle implying that as much as possible of the initial information is regained. Not only the way how humans construct spatial mental models is guided by the asymmetry between the two objects (RO and LO) of a binary relation, but also the way how they regain consistencies in a spatial context. As mentioned before humans make a use of this asymmetry in spatial descriptions and in daily life some objects are more predestinated to be a LO than an RO in a spatial description. This aspect could be fruitful for further investigations since most of the presented studies intentionally avoid this aspect.

A crucial point for the future is a more theoretical one. In the present work the terms “belief” and “model” were used more or less equivalent. Please note that a belief is classified to be more likely based on propositional representations with a truth value (Harman, 1986). In this sense, beliefs are not comparable with models and belief revision should not be the same as model revision. Due to the experimental structure and the theoretical framework, the present work is more concerned with spatial model revision than with spatial belief revision. This issue should be topic of interest of further research in order to bring more theoretical contributions.

All findings in the present study agree with the mental model theory, which claims out assumptions about reasoning processes on the basis of construction, inspection and

variation of spatial mental models. Overall, the present investigations offer a new view on how humans deal with spatial information in different context, how they represent given information, deal with inconsistencies and regain consistencies within a belief set. Crucial theoretical frameworks of the human thought fit well together and show the way forward for further investigations. Altogether, further experiments are needed, because no matter if humans are reading a text, getting a route description, or are confronted with any kind of unrelated information, that does not allow a straightforward integration of all essential pieces of information, it is undisputed that humans have a hard time to cope with it. In a similar vein the revision of spatial beliefs requires different reasoning capabilities and the present work offers some basic principles which in the future can be related to more practical domains. We started with a very first study and adapted the spatial belief revision paradigm to investigate a related domain, way-finding.

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Gießen, den 13.01.2015

(Jelica Nejašmić)