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Cognitive processes underlying spatial belief revision

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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.

Keywords: Spatial reasoning; mental models; belief revision; spatial cognition; relational reasoning; spatial relations

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 (De Vooght & Vandierendonck, 1998; Klauer, 1998; Byrne, 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., 1996; 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), Ragni, Knauff, and Nebel (2005), Rauh et al. (2005), and Rauh et al. (1997) 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" (Harman, 1986; Gärdenfors, 1984). 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 & Baguely (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. 23 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. 32 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 fact[1] (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 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 analysed) 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 98.64% ($SD = 2.27$) of the trials within 1.97s ($SD = 0.75$). Erroneous trials were excluded from further analysis.

[1]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".

Inconsistency detection was successful in 91.75% (*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" ($M = 87.78$ % $SD = 14.38$) as compared to "relocation of the last object" ($M = 12.22$ %; $SD = 14.38$; $t(22) = 12.60$; $p < .001$). 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 preferably 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.

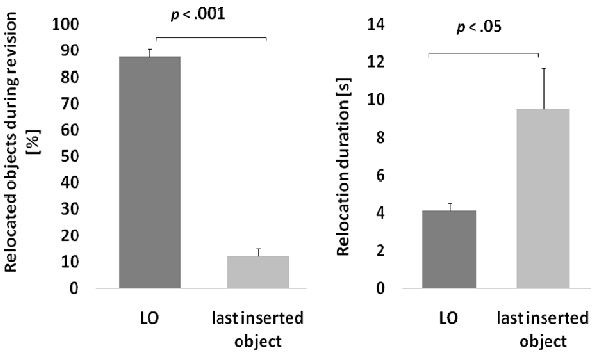

Figure 1. In experiment 1, revision was mainly based on the relocation of inconsistent facts´ LOs. Error bars show standard errors.

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. For that purpose it will be reported in detail elsewhere (Bucher, Krumnack, Nejasmic, & Knauff, submitted). Here, 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. 22 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. 32 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 „left of" and „right of" in the premises and facts in items of experiment 2			
1st premise	left of	left of	right of	right of
2nd 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 analysed) 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 analysed offline after the experimental session.

Results and discussion

Model construction: Mean percentage rate of correctly constructed models was 97.16 % (*SD* = 3.47). Erroneous trials were excluded from further analysis. Participants constructed order 1 – 2 – 3 (*M* = 50.89 %; *SD* = 4.25) comparably often as order 2 – 1 – 3 (*M* = 49.11 %; *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 [$F(1,21) = 82.84$; $p < .001$]. Orders were constructed by putting the first mentioned object of the 1st premise (*M* = 83.28%; *SD* = 17.15) before the second mentioned object (*M* = 16.72%; *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 98.42 % (*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* = 51.26 %; *SD* = 7.77) as second mentioned objects (*M* = 48.74 % *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 as compared to 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* = 89.52 %; *SD* = 11.30). Details are reported in Bucher et al. (submitted).

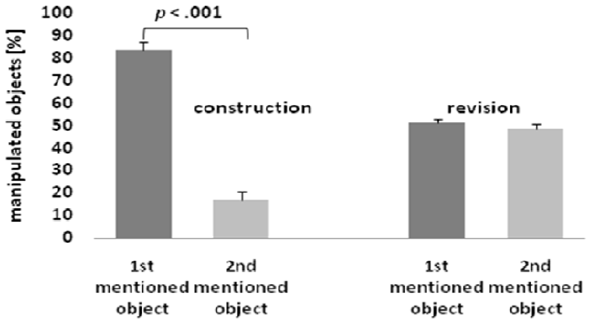

Figure 2. First mentioned objects of relevant spatial information were manipulated first during construction, reflecting an order effect. This order effect was not present during revision. Error bars show standard errors.

Conclusion

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 (Exp. 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 (Exp. 2).

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