Construction and Revision of Spatial Mental Models under High Task Demand

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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.

Keywords: spatial reasoning, spatial mental models, belief revision, episodic trace, memory effect

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 (Johnshon-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:

(3) "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 & Bagueley, 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 extent 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 believes, 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, compared to 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, $t(37) = -4.67$; $p < .001$, $d = 1.54$, compared to the continuous condition. For third premises reading times were longer in the discontinuous condition compared to 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 *p*s > .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
	M (SD)	*M (SD)*	*M (SD)*
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) × 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 *p*s > .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).

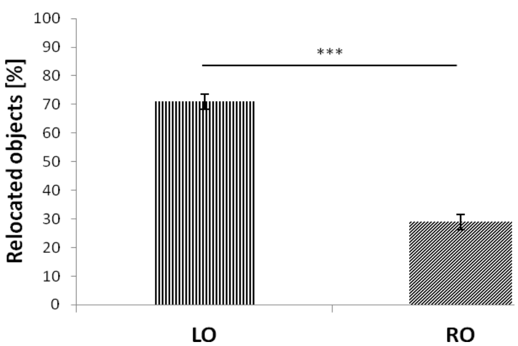

Figure 1: Relative frequency (in %) of model choices based on the relocation of a fact´s LO vs. RO in experiment 1. Error bars show standard errors.

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) × 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 × 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, $t(24) = -4.69$; $p < .001$, $dz = 0.90$, as well as of semi-continuous orders, $t(24) = -4.63$; $p < .001$, $dz = 0.98$. For third premises, reading times were longer in the discontinuous condition than in the continuous, $t(24) = -6.67$; $p < .001$, $dz = 1.23$, as well as semi-continuous condition, $t(24) = -4.58$; $p < .001$, $dz = 0.82$. Equally, participants needed more time for processing third premises of semi-continuous compared to continuous orders, $t(24) = -5.09$; $p < .001$, $dz = 1.00$. All other analyses were non-significant (all *p*s > .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
	M (SD)	*M (SD)*	*M (SD)*
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) × 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 ($M = 58\%$; $SD = 32.3$), $t(24) = 2.52$; $p = .019$, $dz = 0.51$, (see figure 2). All other analyses were non-significant (all *p*s >.15).

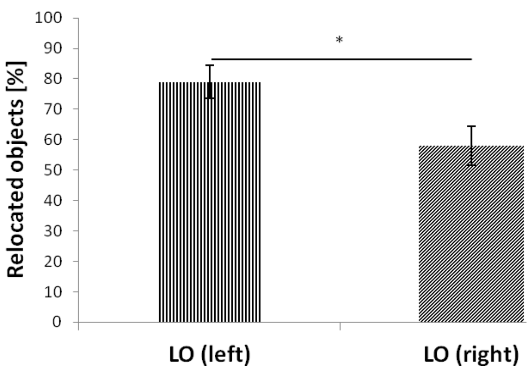

Figure 2: Relative frequency (in %) of model choices based on the relocation of a fact´s LO to the leftmost side vs. the rightmost side of a spatial mental model. Error bars show standard errors.

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 indented 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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