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The construction of spatial mental models—A new view on the continuity effect

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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.

Keywords: Spatial mental models; Spatial cognition; Spatial reasoning; Premise order; Continuity effect

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; Goodwin & Johnson-Laird, 2005; Johnson-Laird, 2001; Johnson-Laird & Byrne, 1991; Polk & Newell, 1995). In other words, it is assumed that people construct an integrated representation

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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 (Goodwin & Johnson-Laird, 2005; Johnson-Laird, 1983; Johnson-Laird & Byrne, 1991; Knauff, Rauh, & Schlieder, 1995; Knauff, Rauh, Schlieder, & Strube, 1998; Ragni, Knauff, & Nebel, 2005; Rauh et al., 2005; Schaeken, Girotto, & Johnson-Laird, 1998; Vandierendonck & de Vooght, 1997).

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; Goodwin & Johnson-Laird, 2005; Halford et al., 1998). 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" (Chan & Bergen, 2005; De Soto, London, & Handel, 1965; Hörnig, Oberauer, & Weidenfeld, 2006; Huttenlocher, 1968; Krumnack, Bucher, Nejasmic, & Knauff, 2010; Krumnack, Bucher, Nejasmic, Nebel, & Knauff, 2011; Spalek & Hammad, 2005). 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; Krumnack et al., 2011; Ragni, Fangmeier, Webber, & Knauff, 2006; Ragni et al., 2005; Rauh et al., 2005; Rauh, Schlieder, & Knauff, 1997). 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 (Baguley & Payne, 2000; Clark, 1969; Ehrlich & Johnson-Laird, 1982; Grosz, Joshi, & Weinstein, 1995; Haviland & Clark, 1974; Huttenlocher, 1968; Oberauer, Hörnig, Weidenfeld, & Wilhelm, 2005; Oberauer & Wilhelm, 2000). 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: (a) Ar_1B, (b) Br_2C, and (c) 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—for example, "A is left of D" (Johnson-Laird, 1972; Knauff et al., 1998; Potts & Scholz, 1975). 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", "semicontinuous", to "discontinuous":

continuous: Ar_1B, Br_2C, Cr_3D *(like in the introductory example)*
semicontinuous: 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 semicontinuous 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 semicontinuous than in discontinuous orders. The effect is known as "continuity effect" (Ehrlich & Johnson-Laird, 1982; Evans, Newstead, & Byrne, 1993; Foos, Smith, Sabol, & Mynatt, 1976; Garnham, Oakhill, & Johnson-Laird, 1982; Knauff, 2006, 2013; Knauff et al., 1998; Potts, 1972; Rauh et al., 1997; Smith & Foos, 1975).

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 (Fodor, Fodor, & Garrett, 1975; Kintsch, 1974). 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 are 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 (Klauer, Stegmaier, & Meiser, 1997; Maybery, Bain, & Halford, 1986; 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; Schaeken, van der Henst, & Schroyend, 2007; Vandierendonck, Dierckx, & De Vooght, 2004). 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* (Goodwin & Johnson-Laird, 2005; Knauff et al. 1995, 1998; Ragni & Knauff, 2013; Rauh et al., 1997) 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; Krumnack et al., 2011; Ragni et al., 2006; Ragni et al., 2005; Rauh et al., 2005; Rauh et al., 1997). Moreover, the preferences result from people's tendency to construct models from left to right (Chan & Bergen, 2005; De Soto et al., 1965; Hörnig et al., 2006; Huttenlocher, 1968; Spalek & Hammad, 2005) 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; Schaeken et al., 2007; Vandierendonck et al., 2004).

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 semicontinuous descriptions that allow the successive construction of a single model.
2. Hypothesis: O*ne* preliminary model is constructed, regardless of the degree of continuity of the premise orders. However, preliminary models based on the nondetermined 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, semicontinuous, and discontinuous premise orders, with the continuous and semicontinuous problems requiring a working direction from left to right. We expected to replicate the continuity effect with Experiment 1 (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 "quasidiscontinuous" 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.

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 analysed) 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, semicontinuous, 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

Table 1. *The premise orders introduced in the experiments*

	Premise order			
	Continuous	*Semicontinuous*	*Quasidiscontinuous*	*Discontinuous*
Experiments	1, 2	1, 2	3, 4	1, 2, 3, 4
Premise 1	Ar_1B	Br_2C	Cr_3D	Cr_3D
Premise 2	Br_2C	Cr_3D	Ar_1B	Ar_1B
Premise 3	Cr_3D	Ar_1B	Dr_2A	Br_2C

(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) × Premise Order (continuous, semicontinuous, 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 × 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 semicontinuous, $t(19) = -2.99$, $p = .008$, $d_z = 0.67$, conditions. Reading times for third premises were highest in the discontinuous condition. They differed significantly from reading times in the semicontinuous, $t(19) = -3.26$, $p = .004$, $d_z = 0.73$, and continuous condition, $t(19) = -3.75$, $p = .001$, $d_z = 0.84$, while reading times in the semicontinuous 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 the second premises, were nonsignificant (all *p*s > .05). See Figure 1 for illustration.

Reasoning accuracy and speed

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

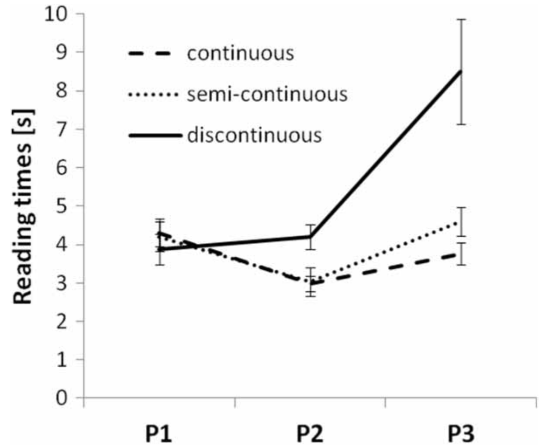


Figure 1. *The "continuity effect" as it occurs in the construction phase. The figure shows Experiment 1's mean reading times for the three premises (P1, P2, P3) depending on the premise orders continuous, semicontinuous, and discontinuous. Error bars show standard errors.*

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 semicontinuous premise orders ($M = 79\%$, $SD = 28.4$), $t(19) = 2.8$, $p = .011$, $d_z = 0.63$. In contrast, performances did not differ between continuous and semicontinuous orders, $t(19) = 1.83$, $p = .082$.

However, participants needed significantly less time to define the correct arrangement when premises were presented in a semicontinuous order ($M = 1.01$ s, $SD = 0.31$) than for continuous ($M = 1.17$ s, $SD = 0.48$), $t(17) = 2.84$, $p = .011$, $d_z = 0.58$, and discontinuous premise orders ($M = 1.24$ s, $SD = 0.44$), $t(15) = -3.87$, $p = .002$, $d_z = 0.19$. 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 semicontinuous 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 nonpreferred 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, semicontinuous, and discontinuous) using the relation "right of", resulting in a working direction from right to left.

Here is an example trial (continuous order):

P1. "Apple right of pear"
M1: pear–apple
P2. "Pear right of mango"
M2: mango–pear–apple
P3. "Mango right of kiwi"
M3: kiwi–mango–pear–apple

The same dependent variables as those previously were of interest.

Results and discussion

Premise reading times

For reading times, an ANOVA with the factors Premise Number (first, second, third) × Premise Order (continuous, semicontinuous, 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 of Premise Number × 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, $t(20) = -3.31$, $p = .004$, $d_z = 0.72$, and, marginally, of semicontinuous orders, $t(20) = -2.36$, $p = .028$, $d_z = 0.52$. All other differences were nonsignificant (all ps > .08; see Figure 2).

Reasoning accuracy and speed

Percentages of correct responses and corresponding response times were compared depending on

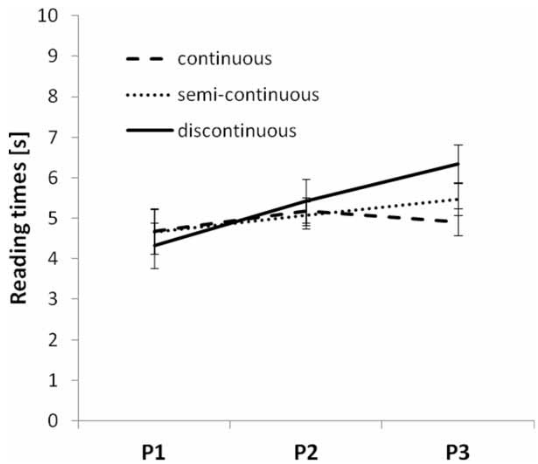


Figure 2. *Experiment 2's mean reading times for the three premises (P1, P2, P3) depending on the premise orders continuous, semicontinuous, and discontinuous. Error bars show standard errors.*

different premise orders (continuous, semicontinuous, 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 semicontinuous 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 semicontinuous 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 semicontinuous 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 show 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 (nonpreferred) 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.

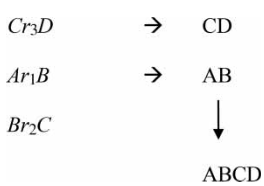
Our results from Experiments 1 and 2 suggest two crucial points—mental processing of not-related spatial information is associated with more cognitive effort, and, second, continuity effects can be modulated by different working directions. It seems that a working direction from right to left inhibits 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; Ragni et al., 2005; Rauh et al., 2005; Rauh et al., 1997).

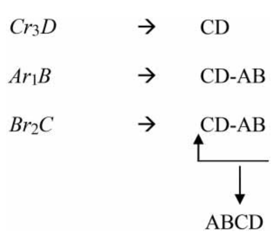
Results from Experiment 2 lead to the assumption that discontinuously presented information is integrated into one model, with a preferred working direction from left to right. If this is the case, it is reasonable that performance differences are not caused by cognitive effort for holding and integrating 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 quasidiscontinuous (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 Experiments 1 and 2), we assume that humans integrate spatial information preferably from left to right into a horizontal linear order (Chan & Bergen, 2005; De Soto et al., 1965; Huttenlocher, 1968; 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 quasidiscontinuous 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 quasidiscontinuous 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 quasidiscontinuous problems will take the same time, and, in addition, no performance differences will occur. In cases where reasoners apply Principle 2, quasidiscontinuous 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 analysed) preceded the experimental trials. The structure of the trials and the procedure were comparable with those of Experiments 1 and 2, whereby premises were presented in the two orders, discontinuous and quasidiscontinuous, 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) × Premise Order (quasidiscontinuous, 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 of Premise Number × Premise Order, $F(2, 38) = 16.9$, $p < .001$, $\eta^2 = .47$. Premise orders did not differ significantly ($p = .062$).

T-tests revealed significantly longer reading times of third premises of discontinuous ($M =$ 9.36 s, $SD = 3.45$) than of those of quasidiscontinuous 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 nonsignificant (all ps > .05).

Reasoning accuracy and speed

Percentages of correct responses and corresponding response times were compared depending on different premise orders (discontinuous vs. quasidiscontinuous) calculating separate ANOVAs.

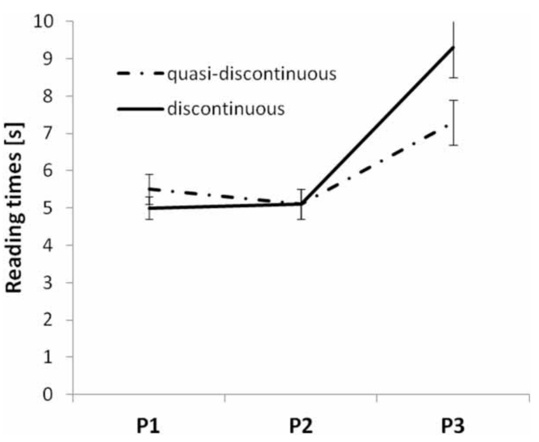


Figure 3. *Mean reading times for the three premises (P1, P2, P3) depending on the premise orders quasidiscontinuous and discontinuous (Experiment 3). Error bars show standard errors.*

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% ($SD =$ 18.7), when premises were presented in a quasidiscontinuous 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 quasidiscontinuous 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 quasidiscontinuous 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 quasidiscontinuous 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 quasidiscontinuous 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 quasidiscontinuous 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 quasidiscontinuous 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 quasidiscontinuous 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 quasidiscontinuous: Cr_3D, Ar_1B, Dr_2A). Six practice trials (not analysed) 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 Premises 1 and 2. This manipulation allows us to test whether links that connect partial models are as strong as links within partial models. For an overview of all third premises used in Experiments 3 and 4 see Table 2.

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 analysed.

Results and discussion

Premise reading times

To analyse the reading times with regard to the respective premise orders (discontinuous vs. quasidiscontinuous) 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 of Premise Number × Premise Order, $F(2, 40) = 11.48$, $p = .001$, $\eta^2 = .37$. Again we focus on the significant interaction.

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

Reasoning accuracy and speed.

Percentages of correct responses and corresponding response times were compared depending on different premise orders (discontinuous vs. quasidiscontinuous), calculating separate ANOVAs. Neither numbers of correct responses (discontinuous: $M = 75\%$, $SD = 22.8$; quasidiscontinuous: $M = 79\%$, $SD = 15.7$) nor corresponding response times (discontinuous: $M = 1.07$ s, $SD = 0.32$; quasidiscontinuous: $M = 1.03$, $SD = 0.30$) 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 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

Table 2. *Overview of formulations of the third premise in Experiments 3 and 4*

	Experiment 3		*Experiment 4*	
	Discontinuous	*Quasidiscontinuous*	*Discontinuous*	*Quasidiscontinuous*
M preliminary	*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

Note: M preliminary is constructed on the basis of Premises 1 and 2.

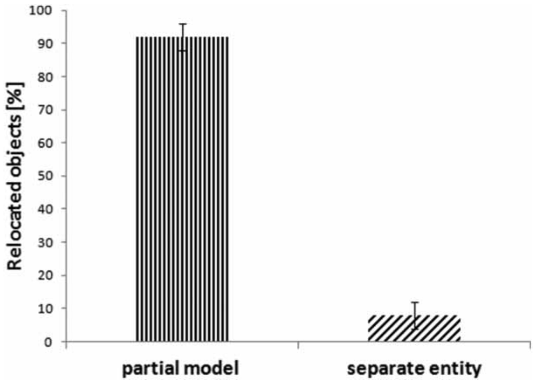


Figure 4. *Percentage rates for given responses in the discontinuous premise order, based on a relocation of a completely partial model compared to a single entity in Experiment 4. Error bars show standard errors.*

(consisting of two entities) were relocated, resulting in the arrangement A–B–C–D (Principle 2), as opposed to the cases where relocations of single entity were performed (Principle 1).

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 semicontinuous 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 quasidiscontinuous problems. It is easier to construct mental models in quasidiscontinuous 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 semicontinuous condition where only one object had to be placed into the "nonpreferred" 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; Krumnack et al., 2011; Ragni et al., 2006; Ragni & Knauff, 2013; Ragni et al., 2005; Rauh et al., 2005; Rauh et al., 1997).

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 nonspatial 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 nonspatial 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 nonspatial relations and nonspatial content (Knauff, 1999, 2013; Prado, Chadha, & Booth, 2011; Prado, van der Henst, & Noveck, 2008). 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 (Ferstl, 2010; Ferstl & von Cramon, 2005; van Dijk & Kintsch, 1983). 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 tell them apart 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) metal 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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