Cognitive processes underlying the continuity effect in spatial reasoning

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Abstract

It is assumed that spatial reasoning about previously obtained information that describe relations between two or more objects is based on the construction and inspection of mental models. The paper mainly focuses on the question how humans integrate spatial information that initially appeared not to be linked. Two experiments investigated the construction processes of spatial mental models and the integration of additional information into existing models. The results show that combining information that are initially not related to one another takes longer and leads to more errors. Then moreover, information presented in a continuous and a semi-continuous order was integrated sequentially, whereas information presented in a discontinuous order was first integrated sequentially into one temporary model and if necessary subsequently revised.

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

Introduction

Imagine the following situation: a new member of staff joins the company and colleague A tells him: “my office is to the right of Leo´s office”, and colleague B tells him: “my office is to the left of Bill´s office”. At first sight, it looks like these two statements have nothing to do with one another. And then he gets to know colleague C who tells him: “Bill´s office is to the left of Leo´s office”. With this additional information it is possible to arrange the offices. Reasoning with non-spatial and spatial relations is an important everyday task. The processes underlying these abilities are not fully understood. In the following we review some crucial aspects of the theoretical assumptions concerning spatial reasoning and present empirical evidence how humans integrate successively presented spatial information into coherent spatial representations.

Theoretical approaches of spatial reasoning

Studies have shown that spatial reasoning most likely relies on spatial representations which reasoners construct in some cognitive space. This is best accounted for by the mental model theory (MMT) which postulates that reasoners use the meaning of assertions and general knowledge to construct single models of possibilities compatible with these assertions (Johnson-Laird & Byrne, 1991; Polk & Newell, 1995; Goodwin & Johnson-Laird, 2005;). This means that people use the linguistic description of a situation for constructing an integrated representation by translating the given information into a mental model. These integrated representations constitute models in the strict logical sense and represent in “small scale” how “reality” could be (Craik, 1943).

According to the mental model theory spatial reasoning relies on the construction and inspection of mental models (e.g. Johnson-Laird & Byrne, 1991; Knauff, Rauh, & Schlieder 1995; Vandierendonck & de Vooght, 1997; Knauff, Rauh, Schlieder, & Strube, 1998; Schaeken, Girotto, & Johnson-Laird, 1998; Ragni, Knauff, & Nebel, 2005; Rauh, Hagen, Kuss, Knauff, Schlieder, & Strube, 2005).

Knauff et al. (1998) have specified three distinct phases for this special case of reasoning: A construction phase, during that reasoners construct a mental model, reflecting the information of the premises, an inspection phase, during which the model is inspected for implicit information of the premises, and a variation phase, during which alternative models are constructed and investigated concerning their compatibility with the information given by the premises. If necessary the third phase results into falsification of the preliminary mental model, constructed during the first phase. The following is intended to clarify some details about the construction processes of integrated spatial mental models.

Construction processes of integrated spatial mental models

Consider the following spatial description:

1. The apple is to the left of the peach.
2. The peach is to the left of the kiwi.
3. The kiwi is to the left of the mango.

These statements are called premises and such a determinate description, using a transitive spatial relation, allows us to create a linear order of the objects named in the premises like apple – peach – kiwi – mango. With such a linear order we can also draw conclusions consisting of information not explicitly given in the premises.

Like in our example, also known as a *four-term series problem (4ts-problem)*, three premises $A\ r_1\ B$, $B\ r_2\ C$ and $C\ r_3\ D$ are given with a spatial relation *r*, like "left of" or "right of". The premises can be presented in a continuous ($A\ r_1\ B$, $B\ r_2\ C$, $C\ r_3\ D$), a semi-continuous ($B\ r_2\ C$, $C\ r_3\ D$, $A\ r_1\ B$) and a discontinuous order ($C\ r_3\ D$, $A\ r_1\ B$, $B\ r_2\ C$) (Knauff et al., 1998). The first two premises presented in a continuous as well as in a semi-continuous order are linked by a middle term which means that one object from the first premise appears in the second premise and so it is possible to integrate the information sequentially. Only the third premise differentiates between these conditions. In a continuous order one object in the third premise appears from the second premise, whereby in a semi-continuous order the third premise is linked to the first premise. In contrast, the second premise presented in a discontinuous order is quite independent of the first premise. Only with the information from the third premise it is possible to integrate all given information.

The outcome of processing these premises are integrated representations in the sense of a mental model and it is easier to construct such a mental model with premises presented in continuous or semi-continuous orders, than in a discontinuous order (Ehrlich & Johnson-Laird, 1982; Knauff et al., 1998). This is also known as the continuity effect, which describes that individuals make more correct inferences, recall the premises better, draw more correct diagrams, are faster when reading the descriptions and drawing inferences when the information are presented in a continuous or semi-continuous order rather than when presented in a discontinuous order (Evans, Newstead, & Byrne, 1993). So in the case of model construction complexity is modulated by the order in which the premises are presented, and the question is how humans deal with information presented in a discontinuous order which cannot be integrated sequentially (Evans, Newstead, & Byrne, 1993).

To explain the continuity effect it is generally assumed that a reasoner, given such a determinate 4ts-problem in a discontinuous order, will create a model from the first premise, another model from the second premise and then integrate those two models into a single model. This implies that reasoners keep these two models separately in working memory and need more time and cognitive effort to create an integrated model. In contrast, in the continuous and semi-continuous order it is possible to integrate the information of the first two premises continuously from the beginning, because of the direct link between premise one and premise two (Ehrlich & Johnson-Laird, 1982; Knauff et al., 1998).

On the other hand, in cases of indeterminate descriptions, i.e. when more than one model can be constructed from the information given by the description, Knauff et al. (1995), Rauh, Schlieder, & Knauff (1997), Ragni et al. (2005), and Rauh et al. (2005) provided evidence that reasoners deal with ambiguous descriptions, by focusing on only a subset of possible models and often just a single one.

Given this tendency to construct a single model that does not comprise all the possible settings it seems plausible that human reasoners would try to create a single model in other situations as well even if the situation cannot be condensed in a single valid model. This could happen during the construction phase of a discontinuous problem, if the information of the second premise is integrated into the model constructed from the first premise. Before we look at this special case of spatial model construction, we first want to investigate the continuity effect.

As said above, there are some evidences that a construction of a mental model is much slower and less reliable when based on premises presented in a discontinuous premise order compared to premises presented in a continuous or semi-continuous order (Ehrlich & Johnson-Laird, 1982; Knauff et al., 1998). In a pre-study we focus mainly on the continuity effect and expect to replicate these results known from previous studies. In the main experiment we want to go a step further and we want to focus more strongly on the construction process based on descriptions with two partial mental models.

Pre-Study

Method

Participants.

25 participants (4 male; age: $M = 22.2$; $SD = 2.5$) all students (among them 4 students of psychology) from the University of Giessen, served as paid participants and gave written informed consent to participation. The data from five participants were excluded from the analysis due an extreme number of errors (n = 2) or extremely long reading times (n = 3). Subjects were tested individually and were paid at a rate of 8 Euro per hour. The experiment took approximately 30 – 45 min.

Materials, Procedure, and Design.

72 determinate 4ts-problems using only the relation "left of" were presented randomly either in a continuous, semi-continuous, or discontinuous order. Three premises (presented sequentially in a self-paced manner) described a one-dimensional linear order of four (small, equal-sized, disyllabic-termed) objects, belonging to either one out of three categories (tools, fruits or vegetables) using the relations. Participants were introduced to imagine the arrangement of the objects named in the premises.

Subsequently to premise presentation participants were instructed to define the correct arrangement by typing the initial letters of the presented objects using the computer keyboard. After the last letter has been entered the trial finished automatically and the next trial started manually by pressing the enter-button. Premise reading times (respective time taken from text onset to button press calling up the next premise) as well as response times (time from request onset to entering the last letter) and the numbers of correct responses were recorded.

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) on a standard personal computer with a 19`` monitor.

Results

To examine whether reading times of the first, second and third premises are contingent upon different premise orders ("continuous order" vs. "semi-continuous order" vs. "discontinuous order"), an ANOVA with the factors premise number (first premise, second premise, third premise) and premise order (continuous order, semi-continuous order, discontinuous order), was conducted. Level of significance was 5%.

ANOVA revealed a significant main effect of premise number [$F(2, 38) = 9.99$; $p < .01$; $\eta^2 = .34$], a significant main effect of premise order [$F(2, 38) = 13.44$; $p < .01$; $\eta^2 = .41$] and a significant interaction premise number × premise order [$F(4, 76) = 10.73$; $p < .01$; $\eta^2 = .36$]. Based on results known from previous studies we expect to replicate the continuity effect, which is described above, and so we are mainly interested in the significant interaction at this point. (Ehrlich & Johnson-Laird, 1982; Knauff et al., 1998).

Premise reading times depending on the premise order were compared, using *t*-tests. Participants needed significant more time for reading second premises presented in a discontinuous order ($M = 4.20$ s; $SD = 1.46$) compared to second premises presented in continuous ($M = 2.99$s; $SD = 0.91$; $t(19) = -4.26$; $p < .001$) or semi-continuous orders ($M = 3.03$s; $SD = 1.64$; $t(19) = -2.99$; $p < .01$). There was no difference between the "continuous" and "semi-continuous" premise orders ($t(19) = -.16$; $p = .876$).

By comparison of reading times of the third premises results show that participants needed significant more time for reading third premises presented in a discontinuous order ($M = 8.50$ s; $SD = 6.15$) than for premises presented in a in a continuous order ($M = 3.76$ s; $SD = 1.25$; $t(19) = -3.75$; $p < .01$) as well as for premises presented in a semi-continuous order ($M = 4.60$s; $SD = 1.67$; $t(19) = -3.26$; $p < .01$). Equally there was a significant difference of reading times of third premises presented in a semi-continuous order compared to premises presented in a continuous order ($t(19) = -3.13$; $p < .01$) (see Fig. 1). There was no difference between reading times of first premises (all *p*s > .05).

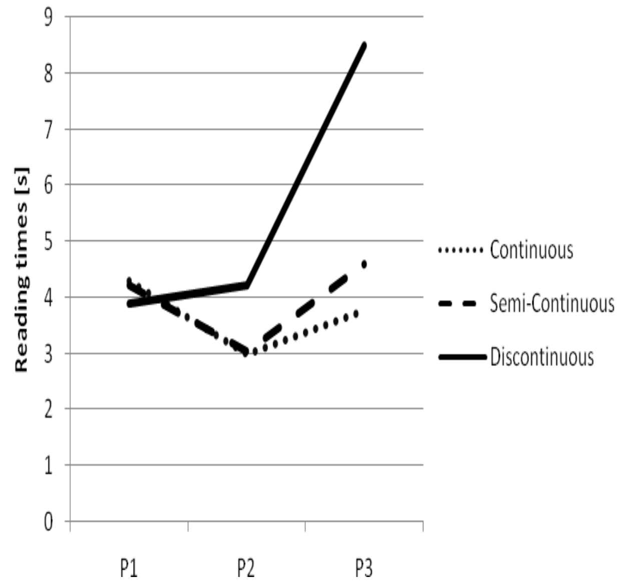

Figure 1. Mean reading times for the three premises depending on the premise order.

Percentages of correct responses and respective response times depending on the premise order were compared calculating separate ANOVAs. Level of significance was 5%. ANOVAs revealed a significant difference for percentages of correct responses [$F(2, 38) = 9.9$; $p < .001$; $\eta^2 = .34$] and response times [$F(2, 30) = 8.42$; $p < .01$; $\eta^2 = .36$].

Participants defined the correct arrangement of objects in 58.5% ($SD = 37.3$) when the premises were presented in discontinuous orders. Compared to the other premise orders these results differ significantly (continuous order: $M = 91.7$ %; $SD = 6.5$; $t(19) = 3.99$; $p < .01$; semi-continuous order: $M = 79.2$ %; $SD = 28.4$; $t(19) = 2.8$; $p < .05$). In contrast to this, percentages of correct responses based on the continuous and semi-continuous order did not differ significantly ($t(19) = 1.83$; $p = .082$).

Responses depending on the premise order "semi-continuous" ($M = 1.01$ s; $SD = 0.31$) took significantly less time compared to responses depending on the premise orders "continuous" ($M = 1.17$ s; $SD = 0.48$; $t(17) = 2.84$; $p < .05$) and the premise orders "discontinuous" ($M = 1.24$s; $SD = 0,44$; $t(15) = -3.87$; $p < .01$). Response times based on continuous order compared to discontinuous order did not differ significantly ($t(17) = -1.45$; $p = .17$).

Hypotheses about construction processes for spatial mental models

Results from the pre-study support the assumption from previous studies (Ehrlich & Johnson-Laird, 1982; Knauff et al., 1998) that processing information which are not related to one another takes longer and leads to more errors. Nevertheless it is not clear how humans process such descriptions and whether they hold the information separately e.g. in two separate models or in one temporary model. To investigate this construction process we conducted the main experiment and present two possibilities how models could be constructed:

1. Information of the first two premises is held separately (and integrated into one model by information provided by the third premise).

2. Information is integrated into one temporary model (that is revised according to the information provided by the third premise, if necessary).

To test which principle (1 or 2) is applied, we presented two types of similar problems based on either discontinuous *(C r_3 D, A r_1 B, B r_2 C)* or quasi-discontinuous *(C r_3 D, A r_1 B, D r_2 A)* premise orders. A discontinuous premise order as well as a quasi-discontinuous premise order implicates that the first two premises are not linked by a middle term.

Up to this point a problem presented in a quasi-discontinuous order is similar to a problem presented in a discontinuous order. The difference between these two conditions becomes evident in the third premise. In contrast to the discontinuous premise order the third premise presented in a quasi-discontinuous order consists of the last term of the first premise and the first term of the second premise. In contrast, the third premise presented in a discontinuous order consists of the last term of the second premise and the first term of the first premise. Thus, both spatial descriptions result in different arrangements (C – D – A – B for the quasi-discontinuous order and A – B – C – D for the discontinuous order).

As already mentioned before, it is assumed that humans keep two models separately in working memory when information are not related to one another and create an integrated model afterwards (Ehrlich & Johnson-Laird, 1982; Knauff et al., 1998). However, there are also indications that reasoners deal with ambiguous descriptions by focusing on only a subset of possible models and often just a single one (Knauff et al.,1995; Rauh et al., 1997; Ragni et al., 2005; Rauh et al., 2005). For the case that reasoners tend to construct one temporary model based on discontinuous descriptions, it is not clear in which way the information of the second premise will be integrated into the model constructed from the first premise. But since the reasoner does not have any information where to integrate the new information, he will have to guess. For example, the information from the second premise could be integrated either to the left or to the right of the partial model constructed from the first premise.

For the construction process there is evidence that relations are integrated either into a vertical or horizontal linear order (De Soto, London, & Handel, 1965; Huttenlocher, 1968) and that the left end of this linear spatial representation is the preferred starting point resulting in a working direction from left to right, reflecting the cultural bias to work in the same direction as reading and writing (Chan & Bergen, 2005; Spalek & Hammad, 2005). This would suggest, that reasoners would preferably construct C – D – A – B as a temporary model for both discontinuous and quasi-discontinuous problems. For quasi-discontinuous problems this model can be confirmed when reading the third premise while for discontinuous problems it needs to be revised.

So we expect different results based on the principles applied, regarding reading times for the third premises and the frequency of mistakes:

- If a reasoner pursues principle (1) the model construction for discontinuous and quasi-discontinuous problems should take the same time and additionally there should be no difference regarding the frequency of mistakes.

- If a reasoner pursues principle (2) when reading the third premise he can then either confirm the temporary constructed order, in case of trials of the quasi-discontinuous condition, or he has to revise the temporary model (as it is the case with discontinuous premise orders). This implies that quasi-discontinuous trials, will take considerably less time than discontinuous trials.

Main experiment

Method

Participants.

21 participants (3 male; age: M = 23.9; SD = 2.8) all students (among them 6 students of psychology) from the University of Giessen, served as paid participants and gave written informed consent to participation. The data from four participants were excluded from the analysis due an extreme number of errors. Subjects were tested individually and were paid at a rate of 8 Euro per hour. The experiment took approximately 30 – 45 min.

Materials, Procedure, and Design.

32 determinate 4ts-problems were presented randomly in a quasi-discontinuous or discontinuous order. Three premises (presented sequentially in a self-paced manner) described a one-dimensional linear order of four (small, equal-sized, disyllabic-termed) objects, belonging to either one out of three categories (tools, fruits or vegetables) using the relations “left of” and “right of”. Participants were introduced to imagine the arrangement of the objects named in the premises.

Subsequently to premise presentation participants were instructed to define the correct arrangement by typing the initial letters of the presented objects using the computer keyboard. After the last letter has been entered the trial finished automatically and the next trial started manually by pressing the enter-button. Premise reading times (respective time taken from text onset to button press calling up the next premise) as well as response times (time from request onset to entering the last letter) and the numbers of correct responses were recorded.

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) on a standard personal computer with a 19`` monitor.

Results

To examine whether reading times of the first, second and third premises are contingent upon different premise orders (“quasi- discontinuous order” vs. “discontinuous order”), an ANOVA with the factors premise number (first premise, second premise, third premise) and premise order (quasi-discontinuous, discontinuous) was conducted. Level of significance was 5%.

ANOVA revealed a significant main effect of premise number [$F(2, 40) = 26.5$; $p < .001$; $\eta^2 = .57$], a significant interaction premise number × premise order [$F(2, 40) = 17.3$; $p < .001$; $\eta^2 = .46$], and no significant difference between premise orders [$F(1, 20) = 3.5$; $p = .076$ $\eta^2 = .15$].

Premise reading times depending on the premise number and premise order were compared, using *t*-tests. Participants needed more time for reading third premises presented in discontinuous order ($M = 9.20$ s; $SD = 3.44$) compared to third premises presented in quasi-discontinuous order ($M = 7.24$ s; $SD = 2.61$; $t(20) = -3.76$; $p < .01$) (see Fig 2.). There was no difference neither of reading times of first premises nor of reading times of second premises depending on the premise orders (all $ps > .07$).

Regardless of the premise order participants needed more time for reading third premises ($M = 8.22$ s; $SD = 3.17$) than for reading first premises ($M = 5.18$ s; $SD = 1.73$; $t(41) = -6.5$; $p < .001$) as well as for reading second premises ($M = 4.98$s; $SD = 1.92$; $t(41) = -6.84$; $p < .001$). There was no difference of reading times of first premises compared to reading times of second premises ($t(41) = 0.9$; $p = .38$).

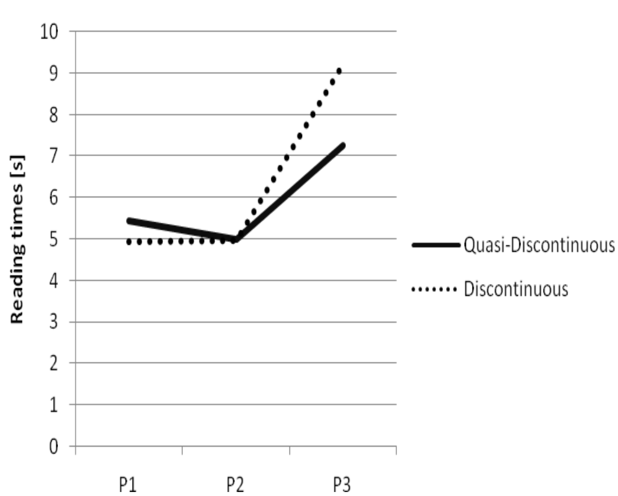

Figure 2. Mean reading times for the three premises depending on the premise order.

Percentages of correct responses depending on the premise orders and respective response times were compared calculating separate ANOVAs. Level of significance was 5%. In contrast to response times ANOVA for percentages of correct responses revealed a significant difference [$F(1, 20) = 6.2$; $p < .05$; $\eta^2 = .24$]. Based on the information provided by the premises presented in quasi-discontinuous orders participants defined the correct arrangement of objects in 76.8% ($SD = 25.3$). In contrast to this, participants defined the correct arrangement of objects in 63.7% ($SD = 30.1$) when the premises were presented in discontinuous orders.

General discussion

Construction of spatial mental models from premises is influenced by various factors. Our study focused mainly on the question how spatial mental models are created especially with respect to discontinuous information. In the pre-study we support previous findings regarding the continuity effect. The results of our experiment add to the body of evidence that dealing with information presented in a discontinuous order is more difficult than dealing with information presented in a continuous or semi-continuous order. So far it was hypothesised that the reason for these differences lies in the two partial models which have to be held separately in memory and could not be integrated before the third premise was presented. To test this we conducted a subsequent experiment and we developed contrasting hypotheses which set a construction process based on two partial models against a construction process based on one temporary model.

The results from the main experiment suggest that different processes are involved when constructing mental models from discontinuous and quasi-discontinuous problems and that mental models are easier to construct from quasi-discontinuous problems than from discontinuous.

Considering the assumption that humans deal with discontinuous information by creating two independent partial models it is reasonable to assume that it would be easier to process the third premise of the discontinuous order compared to the third premise of the quasi-discontinuous order which consists of the last term of the first premise and the first term of the second premise. In the case of the discontinuous order the third premise consists of the last term of the second premise and the first term of the first premise and so the object of interest is already focused and there is no need for a focus shift, so that the new information could be immediately integrated (Hörnig, Oberauer, & Weidenfeld, 2005). This suggests that the differences between discontinuous and quasi-discontinuous orders result from other cognitive processes rather than only from premise processing and integration processes.

The results support the hypothesis that in both cases a single model is formed from the first two premises which then has to be checked for consistency in the light of the third premise. It seems that humans process discontinuous information by creating one temporary mental model rather than by creating two partial models. This implies that the construction of spatial mental models based on discontinuous information is similar to the construction based on continuous as well as semi-continuous information. In the case of the discontinuous problem the model is inconsistent (C-D-A-B) and has to be revised to fit the information of all the premises (A-B-C-D).

However, the question is whether these results can also be explained by the construction of two partial models that are structurally independent but specified in terms of their spatial relation. Assuming that humans construct spatial mental models in a horizontal linear order with the preferring starting point at the left side (De Soto, London, & Handel, 1965; Huttenlocher, 1968) it would mean that the first partial model (C-D) is to the left of the second partial model (A-B) and that there is no need for modifying the arrangement for quasi-discontinuous premise orders. Nevertheless, in both cases the two partial models have to be integrated into one model and in this case the differences in processing would result from the more difficult modification required by discontinuous premises. At this point the question arises whether there are differences between the postulated temporary mental model and two partial models that are structurally independent but specified in terms of their spatial relation.

Taken together, these experiments offer a new point of view to the understanding of the construction processes of spatial mental models.

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