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ARIEL

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Uniform Title:

Author:

Edition:

Imprint: Berlin ; New York : Springer, c1998-

Article: :

Vol: IV

No.:

Pages: 165-180

Date: 2004

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Reasoning About Consistency with Spatial Mental Models: Hidden and Obvious Indeterminacy in Spatial Descriptions

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Abstract. The assessment of whether a statement is consistent with what has gone before is ubiquitous in discourse comprehension. One theory of the process is that individuals search for a mental model of a situation in which all the statements in the discourse are true. In the case of spatial descriptions, individuals should prefer to construct models, which retain the information in the description. Hence, they should use strategies that retain information in an efficient way. If the descriptions are consistent with multiple models then they are likely to run into difficulties. We report some preliminary results of experiments in which the participants judged the consistency of spatial descriptions. The participants made more errors when later assertions in the description conflicted with the preferred models of earlier assertions.

1 Reasoning About Consistency with Mental Models

Sometimes, it is hard to make sense of a description. Imagine, say, that you receive a report about a car accident. One car hit another at a complex crossing. First, you get a description of the crossing, then you are told about the movements of the two cars. But, as you imagine the layout of the crossing and the trajectories of the cars, it seems that they would never have collided. If you have a written report, you can step back and see whether at any point it was possible to interpret the report differently. However, if you listened to the report and did not take notes, it is nearly impossible to consider alternative possibilities. You probably cannot remember exactly what was said. There might be an alternative interpretation of the description in which the cars did collide. Then the whole report would be consistent, even though you had difficulty in understanding it. But sometimes, descriptions just do not make sense. The author of the report may have accidentally used "left" instead of "right" at some point, and so the

C. Freksa et al. (Eds.): Spatial Cognition IV, LNAI 3343, pp. 165–180, 2005.

report in fact was inconsistent. In general, the comprehension of a description and the evaluation of its consistency calls for a search for a possible interpretation. In this article, we briefly summarize what is known about the processing of ambiguous spatial descriptions. Then, we report preliminary results of two experiments that tested predictions about what determines the difficulty of judging the consistency of a spatial description. Finally, we discuss the consequences of our findings for accounts of indeterminacy effects in human spatial reasoning.

Spatial descriptions are often consistent with more than one spatial layout. In everyday discourse, this indeterminacy is usually not a problem, because either the exact spatial relations are unimportant, or common knowledge and conventions allow the indeterminacy of a description to be resolved. Hence, even if a description yields alternative interpretations, different recipients usually arrive at compatible interpretations. One account of the interpretation of spatial descriptions is provided by the theory of mental models (Johnson-Laird, 1983; Byrne & Johnson-Laird, 1989)[1, 2]. In terms of the theory of mental models, when individuals understand a spatial description, they construct a mental model of a state of affairs that is consistent with the description. They begin the model as soon as they receive information, and they integrate further information building on the model as it has been constructed up to this point. It follows that the initial mental model should have a crucial influence on the subsequent interpretation of the discourse. A direct consequence of the updating of mental models is that a difficulty arises when new information is not consistent with the model constructed so far. There might be another model of the information presented so far that is consistent with the new information, but this model may be hard to find. The model theory accordingly predicts that the evaluation of the consistency of a set of assertions should be more difficult if a mental model of earlier assertions is contradicted by a later assertion. In this case, individuals need to search for an alternative model consistent with the complete description (Legrenzi, Girotto, & Johnson-Laird, 2003; Johnson-Laird, Legrenzi, Girotto, & Legrenzi, 2000)[3, 4].

What determines which will be the initial mental model if there are several possibilities? In everyday discourse, prior knowledge and conventions may determine the choice among alternative interpretations. In the example about the car accident, individuals take for granted that the familiar regulations governing driving hold. They may imagine, for instance, that drivers keep to the left-hand side of the road. Hence, it would be difficult for them to construct a model of a crash in which one of the drivers turned left. In a more formal task with schematic descriptions, similar phenomena can influence the choice of the initial mental model and consequently can determine whether or not individuals detect an inconsistency.

1.1 Preferences for Certain Sorts of Spatial Models

When a spatial description is indeterminate, individuals tend to make one sort of interpretation rather than another. They prefer one sort of spatial model to another. For indeterminate descriptions of spatial intervals, such as:

The green interval overlaps the blue interval from the left
The blue interval overlaps the red interval from the left

individuals show a consensus in the sort of model that they envisage (Knauff, Rauh, & Schlieder, 1995; Knauff, 1999)[5, 6]. The two assertions above result in a spatial model, in which the green interval ends before the red interval starts. The other possible models - in which the green interval meets or even extends into the red interval - are systematically neglected by the participants. This example illustrates a more general principle that characterizes preferences for models of spatial intervals. As far as possible, individuals try to keep the linear ordering of start points (green, blue, red in the example) also for the linear ordering of endpoints in models of spatial intervals (linearization). In this way, they minimize the amount of information that they have to keep in working memory.

In everyday descriptions, indeterminacy arises in various ways. The following description:

The hammer is to the left of the saw
The saw is to the right of the drill

is consistent with two arrangements:

hammer drill saw
drill hammer saw

Presumably, there is a preference that biases towards <hammer drill saw>. Individuals seem to place the two objects that are mentioned in the second assertion, saw and drill, adjacent to each other in the model. We assumed this preference for adjacency, which has also been implemented in computer simulations of reasoning with spatial mental models (Johnson-Laird, 1983; Payne, 1993)[1, 7], and constructed a subset of the experimental reasoning tasks accordingly.

There are also spatial prepositions that convey indeterminacy more directly, because they are inherently indeterminate. "Next to" can be used to present an indeterminate description in a single assertion. If "The hammer is next to the saw" refers to a horizontal layout, it is consistent with <hammer saw> and with <saw hammer>. We are going to report evidence that these two possibilities are not equally probable to be chosen as an initial mental model. We will show that <hammer saw>, the ordering that matches the order of mention in the premise, is the preferred alternative. Likewise, indeterminacy can be conveyed with "between". The following assertion:

The hammer is between the drill and the saw

is consistent with two possible horizontal layouts:

drill hammer saw
saw hammer drill

Only <drill hammer saw> reflects the order of mention of drill and saw in the assertion and is the preferred mental model as will be shown.

1.2 Reasoning Problems with Contradicted Preferred Models

In the following experiments, we built on the two supposed preferences: order of mention and adjacency. We constructed reasoning problems that should be difficult, because a preferred mental model is first endorsed in a sequence of assertions, but gets contradicted later on. The experimental task is to evaluate whether the set of assertions is consistent, that is whether there is a one-dimensional layout for which all assertions are true. In the following, we refer to the reasoning problems as Cons1A, Cons1B, Cons2A, Cons2B, Cons3A, Cons3B, and Incons1A, Incons1B, Incons2A, Incons2B. The prefixes "Cons" and "Incons" indicate consistent or inconsistent descriptions, respectively. "A" and "B" refer to the two versions of each problem, for consistent problems this indicates hidden (A) and obvious (B) indeterminacy (see below). Consider the sequence of assertions in problem Cons3A in Table 1. The third column shows the supposed mental model after reading the respective assertion, the fourth column shows the possible layouts that are all consistent with the assertions presented up to this point.

The first assertion in Cons3A, "C is next to D", should yield CD as the preferred mental model. The second assertion, "B is between D and A", can be integrated without changing the order CD and yields CDBA, but the third asssertion, "D is to the right of A", contradicts this preferred mental model. In the problems Cons1A and Cons2A it is the fourth assertion that contradicts the preferred mental model. Presented in a different sequence, the same sets of assertions should be easier to recognize as consistent.

1.3 Reasoning Problems with Obvious Indeterminacy

The supposedly easier sequences are listed as problems Cons1B, Cons2B, and Cons3B in Table 1. They should be easier, because the alternative possibilities are more obvious in the first two assertions. Furthermore, the first two assertions can be represented in a way that supports reorganizing the mental model. Consider problem Cons3B that starts with "B is between D and A" and "C is between D and A". The assertions match with regard to the relation term "between" and the arguments D and A. They invite to construct the relation "being between D and A" ad hoc and to represent that it applies to both, B and C. In terms of relational complexity theory (Halford, Wilson, & Phillips, 1998; Birney & Halford, 2002)[8, 9] this ad hoc simplification of relations is a case of strategic chunking. In this way, individuals reduce the number of variables in relational assertions to be used in steps of the reasoning process (reduction of dimensionality). By means of reducing the number of variables, humans cope with demanding relational reasoning problems when this is possible.

In terms of the theory of mental models, the integrated model of the first two assertions of problem Cons3B consists of one pair of object tokens in between another pair of object tokens and an annotation that the order in both object pairs is not fixed. The parentheses in the third column of Table 1 have been inserted to convey the supposed structuring of the model: D(BC)A. With this model, it is easy to integrate the third assertion, which fixes the order of the outer pair, and also the fourth assertion, which fixes the order of the inner pair.

Table 1. Consistent and inconsistent problems. Assertions of consistent problems occur in two sequences. In A-sequences (Cons1A, Cons2A, Cons3A) a preferred mental model gets contradicted by a later assertion, in B-sequences indeterminacy is obvious and integration of assertions is easier

Problem	Premises	Mental Model	Possible Layouts
Consistent Problems			
Cons1A	C right of B	BC	1: BC
	D right of C	BCD	1: BCD
	D right of A	BCAD	3: BCAD BACD ABCD
	B right of A	ABCD	1: ABCD
Cons1B	D right of C	CD	1: CD
	D right of A	(CA) D	2: CAD ACD
	C right of B	(BC A) D	3: BCAD BACD ABCD
	B right of A	ABCD	1: ABCD
Cons2A	C between D and A	DCA	2: DCA ACD
	B right of A	DCAB	4: DCAB ACDB ABCD ACBD
	D next to C	DCAB	3: DCAB ACDB ABCD
	B next to C	ABCD	1: ABCD
Cons2B	C between D and A	DCA	2: DCA ACD
	B next to C	D (BC) A	4: DBCA DCBA ABCD ACBD
	B right of A	A (BC) D	2: ABCD ACBD
	D next to C	ABCD	1: ABCD
Cons3A	C next to D	CD	2: CD DC
	B between D and A	CDBA	4: CDBA DCBA ABCD ABDC
	D right of A	ABCD	2: ABCD ABDC
	C between D and A	ABCD	1: ABCD
Cons3B	B between D and A	DBA	2: DBA ABD
	C between D and A	D (BC) A	4: DBCA DCBA ABCD ACBD
	D right of A	A (BC) D	2: ABCD ACBD
	C next to D	ABCD	1: ABCD
Inconsistent Problems			
Incons1A	A right of B	BA	1: BA
	C between D and B	DCBA	4: DCBA BCDA BDAD BACD
	D right of C	BACD	3: BACD BCDA BCAD
	B right of A	inconsistent	0
Incons1B	A right of B	BA	1: BA
	C between D and B	DCBA	4: DCBA BCDA BDAD BACD
	D left of C	DCBA	1: DCBA
	B right of A	inconsistent	0
Incons2A	B between A and C	ABC	2: ABC CBA
	D next to C	ABCD	4: ABCD ABDC DCBA CDBA
	B next to D	ABDC	2: ABDC CDBA
	C next to A	inconsistent	0
Incons2B	B between A and C	ABC	2: ABC CBA
	D between B and C	ABDC	2: ABDC CDBA
	B next to D	ABDC	2: ABDC CDBA
	C next to A	inconsistent	0

1.4 Predictions from Model Preferences and Obvious Indeterminacy

Several predictions can be derived from the mental models account of evaluating consistency and from the supposed model preferences. First, if indeterminacy that is introduced in the first assertion of a spatial description cannot be easily represented in a mental model, a single mental model is constructed sequentially. Probably, the single model is the one that conforms with the supposed model preferences. If a later assertion contradicts the preferred model, individuals should have difficulty to find an alternative model that would be consistent with all premises. Therefore, the A-sequences of the problem types Cons1-3, which first support the preferred mental model and contradict it later on, should be difficult.

Second, if indeterminacy is obvious in the first assertion and can be easily represented in a mental model with associated and movable tokens, it should be easier to find a model that is consistent with all assertions. Therefore, the corresponding B-sequences Cons1B, Cons2B, and Cons3B should be less difficult.

And finally, the contrast between consistent problems with preferred models that get contradicted (consistent A-sequences) and problems with obvious indeterminacy (consistent B-sequences) should be more pronounced, if the premises are presented serially. If all premises are presented together, it is possible to start anew with an alternative model and the order of assertions presumably has less effect.

We tested these predictions in two experiments. We report a brief summary of these experiments and selected preliminary results. A full report will be published after additional experiments have been completed. In both experiments, participants evaluated the consistency of consistent and inconsistent premise sets. Each of three consistent sets of assertions was presented in a sequence that contradicted a preferred model (A-sequence) and in a sequence leading to obvious indeterminacy (B-sequence). The two inconsistent sets of assertions were also presented in two variants, but the assertions in the A- and B-sequences of inconsistent problems differed as can be seen in Table 1.

In Experiment 1, assertions were presented serially and reading times were collected to see which assertions are harder to integrate and when difficulty arises. In Experiment 2, assertions were presented in parallel and participants were allowed to draw sketches. Drawing was recorded on video and provided information on the possibilities that were considered first. We expected participants to start with the possibilities that correspond to the presumed preferred models.

2 Experiment 1 - Evaluating the Consistency of Serially Presented Sets of Assertions

In Experiment 1, participants judged the consistency of the problems listed in Table 1 and of analogue problems which contained "left of" instead of "right

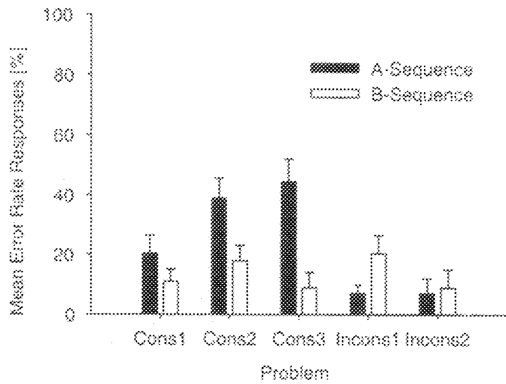

Fig. 1. Mean error rates of consistency judgments for consistent and inconsistent problems in Experiment 1 ($N = 27$); error bars denote the standard error

of". Each consistent set of assertions was presented in two sequences, one that should yield an initial mental model that got contradicted later on (consistent A-sequences) and a second one that should ease the representation of indeterminacy when reading the first assertions (consistent B-sequences). There were consistent and inconsistent sets of assertions. For consistent problems, we expected the A-sequences to cause more errors, the consistent B-sequences should lead to less errors.

The problems were presented self-paced on a LCD screen. Each trial began with the presentation of the first two assertions, each assertion in a separate line. With the space-key, participants could request the third and then the fourth assertion, which were presented separately. Participants were instructed to judge with response keys labeled "Yes" and "No" whether there was a layout for which all four assertions were true.

As expected, error rates showed that consistent problems were harder, if later assertions contradicted a preferred model of earlier assertions (consistent A-sequences). Mean error rates for consistency judgments are shown in Figure 1. For all three consistent problems, the error rates are higher for A-sequences.

For inconsistent problems, error rates were lower than for consistent problems. For the Incons1 problems, error rates were lower for the A-sequence, in which the preferred model gets contradicted. Presumably, the contradiction of the preferred model caused participants to more often judge the set of assertions correctly as inconsistent. For the Incons2 problems, in which such a contradiction was not expected for either sequence, there was no significant difference in response error rates.

Reading times for the first two assertions provided evidence on whether the advantage in representing the information in the first two assertions of consistent B-sequences occurred as predicted. The first two assertions were presented together and their information had to be retained. Participants had to stay aware of possible alternatives. They may have tried to retain the assertions verbally. But more probably, they constructed one possible model and tried to remember in addition how this model could be changed so that it still would be consistent with the information in the premises. The expected advantage for B-sequences was confirmed for Cons1 and Cons3 problems. The reading times of the first two assertions of B-sequences were around 8 s shorter than for A-sequences. For Cons2 problems the advantage was only small (2 s).

The B-sequences were constructed to ease the encoding of multiple possibilities. Matching relations and terms in the first two assertions made it possible to construct simplified relations ad hoc as proposed by Halford et al. (1998)[9]. In terms of the theory of mental models, matching assertions made it easier to construct suitable annotated models. Presumably, in initial models of B-sequences, indeterminacy was represented by inner and outer pairs of object tokens with the annotation that the order within the pairs was unspecified. This was also possible for Cons2B, although the relations in the first two assertions did not match. Verbally, participants may have used the integrated relation "Both, C and B are between D and A".

Experiment 1 confirmed the predicted difficulty of consistent A-sequences and showed that participants had the expected advantage in coping with indeterminacy in consistent B-sequences. In order to collect more direct evidence for the preferences that presumably caused the difficulty of consistent A-sequences, we observed participants' sequential consideration of layouts in Experiment 2. Participants saw all premises of a problem at once and were encouraged to draw sketches of the layouts they considered while evaluating a set of assertions.

3 Experiment 2 - Parallel Presentation and Sequential Drawing

In Experiment 2, participants evaluated the same consistent problems as in Experiment 1. However, instead of reading sequentially presented assertions on a screen, they received all four assertions of a problem at once on paper. They were encouraged to think aloud and to draw sketches. We recorded their drawing on video. Participants should start with the layouts that correspond to the presumed preferred models in Experiment 1. Furthermore, error rates should be diminished with parallel presentation of assertions, because participants could refer to all the assertions during the entire solution process.

The A- and B-sequences of Cons1, Cons2, Cons3, and Incons2 problems in Table 1 were used. Each participant evaluated eight problems. Problem sheets were prepared with the four assertions of one problem printed on the top and free space below for drawing sketches. The experimenter handed the problem sheets to participants one sheet at a time. Participants were encouraged to draw sketches and were prompted to comment on what they did. A video camera was positioned above the desk and recorded the drawing and participants' verbal comments. The purpose of this procedure was explained to the participants and they gave their consent before the experiment started.

The coding of video recordings and answer sheets yielded frequencies for preferred interpretations of assertions. We were interested in how often the layouts considered first were the ones consistent with the order of mention in the first premise and how often adjacency was reflected in the drawings. The first assertion of Cons3A states a "next to" relation and 70.8% of participants' initial drawings that could be coded for Cons3A conformed with the order of mention in the assertion. For first assertions stating a "between" relation (Cons2, Cons3B, and Incons2), 80.2% of initial drawings were consistent with the order of mention. Therefore, the analysis of initial drawings confirmed that order of mention determined the preferred interpretation of first assertions that stated "next to" and "between" relations.

Adjacency should take effect in Cons1A problems. The layouts considered first after reading the third assertion of Cons1A problems were relevant for the question of whether participants preferred adjacency in integrating the third assertion. Only 28.0% of the drawing recordings unequivocally showed that the layout predicted by the adjacency assumption was considered first. However, the variety of participants' strategies that were obvious in the drawings and video recordings might have prevented that a preference for adjacency showed up.

A preference for adjacency was shown, if the first layout that participants considered for Cons1A after the third assertion "D is to the right of A" was the one in which A is adjacent to D, that is BCAD rather than BACD or ABCD (Participants did not use "A, B, C, D" but instead the initial letters of the objects in the presented assertions). The drawings often could not reflect adjacency, because participants' drawing strategies evoked by the parallel presentation of assertions counteracted a possible adjacency effect. When reading the third assertion, their drawings up to this point often differed from a simple notation of BCD, which is the single possible layout consistent with the first two assertions. For example, 3 of the 25 participants first wrote separate pairs of letters for each assertion of Cons1 problems in a vertical alignment. Then they constructed the final layout in a single line. In addition, even if simply BCD was drawn, several participants considered the third and the fourth assertion ("D is to the right of A" and "B is to the right of A") before adding the fourth letter. Therefore, no drawn layout could be observed for the integration of the third assertion alone. For example, five participants just wrote one line while integrating the assertions sequentially and left space initially to fill in the letters for later assertions. These participants might have considered the adjacency layout first, but their drawings were not informative on this point.

For the other problems there was also a variety of strategies reflected in the drawings. Many participants never or seldom layed out all possibilities systematically, but instead added information and corrections to a single layout or started anew to draw the solution.

As expected, the parallel presentation of assertions reduced error rates. They lay between 8% and 32% for consistent problems. Inconsistency was always detected. The video recordings showed that participants usually checked their solution against the assertions and therefore changed some wrong solutions before giving the final answer.

Experiment 2 was conducted to collect evidence for the order of mention and adjacency preferences. The analysis of video recordings confirmed that the layouts most frequently considered first corresponded to the supposed preferred models for "next to" and "between" relations. As expected, with problems that began with "next to" or "between", participants more often started with the layouts in which the order of objects matched the order of mention in the first assertion.

Although all assertions of a problem were accessible at once in Experiment 2, participants usually considered the assertions one after the other in the sequence in which they were printed on the problem sheet. Consequently, with A-sequences they were initially biased toward a layout that preserved the order in which objects were mentioned in the first assertion. They had to change this preferred model to arrive at consistency with later assertions. With B-sequences, obvious indeterminacy as in Experiment 1 counteracted the order of mention preference and increased participants' awareness of alternative possibilities.

Our experiments provided indirect evidence for the adjacency preference by showing that Cons1A was more difficult than Cons1B. However, more direct evidence can be expected from an experiment, in which only the first three assertions are presented and participants are instructed to draw a consistent layout. Such an experiment is currently under way.

4 Model Preferences and Strategies in Spatial Relational Reasoning

In the reported experiments, we tested effects of model preferences in evaluating the consistency of sets of spatial assertions. According to the theory of mental models, humans evaluating the consistency of a set of assertions search for a consistent model. As soon as they encounter the first assertion, they start to construct a model to represent the information contained in the assertion. The initial model is then extended and changed to account for information in later assertions. As a direct consequence of this process, the search for a consistent model can go astray, if earlier assertions support one possibility, but a later assertion contradicts the model constructed so far and requires to consider alternative interpretations of earlier assertions. In Experiment 1 the sequential consideration of assertions was ensured by serial visual presentation. Sequences, in which later assertions contradicted the preferred model of earlier assertions, were harder to evaluate as predicted. In contrast, the same sets of assertions were more often evaluated correctly, if they were presented in sequences whose first assertions revealed indeterminacy and could be more easily represented in a way that allowed participants to stay aware of alternative interpretations.

For problems with contradicted preferred models, we postulated two model preferences. The preference for the order of mention was confirmed in both experiments. If the first assertion was of the form "A is next to B", participants thought of AB rather than BA, and if the first assertion had the form "B is between A and C", participants thought of ABC rather than CBA. They preferred the order that matched the order in which objects were mentioned in the assertions. The reason for this preference is not entirely clear, but most likely it reflects a convention for spatial descriptions that is rooted in the culturally determined habit to visually scan from left to right.

4.1 Causes Underlying the Order of Mention Preference

Imagine, someone would utter a sentence similar to a "next to"-assertion to describe a spatial layout of two objects to somebody else who cannot see the layout or is facing the layout from the same side. The object next to which an assertion locates the other object is the reference object. For instance, in "The hammer is next to the saw", the saw is the reference object. If no object in particular qualifies as reference object, the speaker is not constrained by the conventions regarding the choice of reference objects (e.g., salient, inanimate, stable). Rather, the speaker is influenced by the order in which one encounters the objects if the layout is visually scanned. In Western cultures, people visually scan, read, and write from left to right. In a recent study, participants were asked to formulate a question referring to one of two identical looking objects that they should imagine to be in front of them both equally distant. The objects and the participants' imaginary location were depicted in a diagram (Mainwaring, Tversky, Ohgishi, & Schiano, 2003, Experiment 3)[10]. Participants could freely choose to which object they referred with their question. A majority of participants from the US referred to the left object, however Japanese participants tested in Japan more frequently referred to the right object. This suggests that the direction of visual scanning (left to right in the US, whereas right to left in Japan) determines the order in which equivalent objects are mentioned in a spatial description (prior to cultural experience, the preference seems to be left to right as studied by Tversky, Kugelmass, & Winter, 1991)[11]. The strategy to take recipients on a "gaze tour" is a known strategy in describing, for example, the interior of rooms (Linde & Labov, 1975)[12]. The convention to describe a layout in the order in which it is visually scanned may induce the preference to interpret indeterminate spatial assertions with a preference for the order of mention.

Even if participants did not expect conventional descriptions, visually scanning from left to right might have caused model construction proceeding from left to right (see also Huttenlocher, 1968)[13]. If participants entered the objects in mental models from left to right as they were mentioned, this resulted in a order of mention preference. In a study, in which participants were asked to draw a map according to a description they had learned before, they drew the locations in the map in the order that matched the order of mention in the text (Taylor & Tversky, 1992; see also Spivey, Tyler, Richardson, & Young, 2000)[14, 15]. Presumably, participants in our experiments, even in Experiment 2 with parallel presentation, similarly not only considered assertions one after the other in the presented order, but also the objects mentioned in an indeterminate assertion.

Some predictions can be derived from the order of mention effects that are worth to be tested. First, the difficulty of sequences of assertions in which the preferred model is only induced by order of mention (Cons3A) should not exist for participants who read texts and scan images from right to left. Second, with vertically oriented layouts, there should be no differential effects of the habitual direction of visual scanning and difficulty from the order of mention preference should be found independently of cultural background. And finally, there should also be no differential effect of the direction of visual scanning, if the problems are formulated with relations from non-spatial domains, for example temporal relations.

4.2 Causes Underlying the Adjacency Preference

The second supposed preference in the reported experiments was a preference for adjacency in model construction. If a "left of"- or "right of"-assertion related a new object to an object already in the model, we expected participants to place the new object adjacent to the reference object. Such a bias for adjacency might reflect another convention in spatial descriptions. Speakers describing a layout of objects by means of "left of" or "right of" would choose an adjacent object as reference object (if no other object is a more salient reference object). The reported experiments provided first evidence for an adjacency preference, because predictions on difficulty from adjacency were confirmed. However, participants' drawings were not informative with regard to an adjacency preference for reasons explained in Section 3.

4.3 Representing Indeterminacy

The order of mention and adjacency preferences caused difficulty in detecting consistency, because they biased participants toward a model that was different from the single consistent solution. Participants knew that they needed to find just one consistent layout to answer "consistent". They also knew that to answer "inconsistent" they had to check alternative interpretations of earlier assertions, if later assertions did not fit the interpretation that they had chosen earlier. Therefore, they attempted to retain the information in assertions in addition to a single possible interpretation.

We have designed the problems to yield the representation of indeterminacy more or less difficult. With problems that should induce preferred models, the representation of indeterminacy was difficult, because either multiple mental models were necessary or the necessary propositional annotations to a single model were complex (Johnson-Laird, 1983)[1]. Both, multiple mental models as well as multiple propositional annotations are difficult to retain in working memory. It would have been also difficult to retain the assertions verbally while integrating assertions.

Several terms in the literature convey the idea that indeterminacy may be represented in mental models, for example, by *annotations* (Johnson-Laird, 1983; Vandierendonck, Dierckx, & De Vooght, in press)[1, 16], *isomeric models* (Schaeken, van der Henst, & Schroyens, in press)[17], or *mental footnotes* (Rauh, 2000)[18]. Strategies for representing indeterminacy probably differ between participants. The short description of drawing strategies in the discussion of Experiment 2 may have given an idea of the variability to expect. Despite the variety of participants' strategies, we succeeded in demonstrating that certain sequences of assertions support humans in representing indeterminacy.

The spatial relations that have been most extensively used in experiments on human spatial reasoning are relations such as "left of" or "in front of". They fix the order in a layout and project a direction into a spatial scene. The interpretation of those relations requires the consideration of reference frames (left of the speaker, or left of the recipient, or left of an object with a defined front side, or left of an object with a defined front seen from the viewpoint of the recipient; e.g., Levinson, 1996)[19]. It is true that with these relations any attempt to annotate a mental model in order to represent indeterminacy will exceed working memory after a few assertions. However, an effective annotation was possible for indeterminate relations as they were used in the reported experiments.

The relations "next to" and "between" can be interpreted independently of a reference frame (topologically). In the context of a one-dimensional layout, they directly convey indeterminacy even with the order of mention preference biasing towards one possibility. "Next to" allowed to treat the two related objects as one chunk and consequently as one token in a model as long as no asserted relation such as "left of" fixed their order. Moreover, because participants knew that the layouts consisted of four objects, "between" made further chunking possible. If a combination of premises identified the inner and outer pairs of objects, a model with two tokens for the pairs and annotations specifying which was the outer pair and that the order in both pairs is unspecified was sufficient to correctly represent all four possible layouts. Such chunking and ad hoc reduction of complexity may be seen as an instance of the general strategies for reducing demands that are postulated in relational complexity theory (Halford et al., 1989)[9]. Given the domain of spatial reasoning, participants presumably have constructed spatial representations beyond orderings on one dimension. Human visuo-spatial abilities are manifold (Barsalou, 1999)[20]. Participants did not have to restrict themselves to one-dimensional models and detached tokens. Rather, we suppose that participants used models with combined tokens and a representation of the possible changes of the model conceivable as flipping or rotating pairs of objects.

Chunking and strategic representation of indeterminacy was induced by the demands of Experiment 1, in which participants were not allowed to draw sketches or to take notes of sequentially presented assertions. The effort of strategic chunking was mainly invested in Experiment 1 when it was necessary to reduce processing load. However, in Experiment 2, the strategies we observed in the video recordings of participants' drawing were straightforward notations of possible orders in layouts.

With the use of the indeterminate spatial relations "next to" and "between" we were able to demonstrate effects of model preferences and of strategic reductions of relational complexity in deductive reasoning with mental models. Human spatial relational reasoning has been mainly studied with relations such as "left of" that determine the order of two arguments on a single dimension. One reason for this is that those (asymmetric) relations correspond to common relations in other domains (for example, better, heavier, later). Hence, results obtained with those spatial relations probably generalize to relational reasoning in other domains. Effects that are known for those relations were surely effective in the present experiments, too. Integration of assertions with relations such as "left of" is easier, if the term with which an assertion refers back to the previous assertion has the role of the reference object (relatum = given) and if this term is mentioned first (given-new) as has been shown in a recent study that successfully joined several earlier findings (Hörnig, Oberauer, & Weidenfeld, in press)[21]. However, these order effects cannot explain the large sequence effects in the reported results. Those resulted from model preferences and the support for representing indeterminacy.

We have shown that indeterminate relations such as "next to" and "between" are suitable and practical to study how humans cope with indeterminacy in relational reasoning. In the temporal domain, the equivalent relations are "at the same time as" and "between". In other domains "as R as" is not uncommon and "between with regard to Rness" may be uncommon in language, but seems to be used by individuals in relational reasoning. Therefore it is worthwhile to use indeterminate relations more often in studies of deductive reasoning. In the spatial domain this would also meet the prevalence of indeterminate relations in everyday spatial language. For example, if given the choice between referring to a layout with "left/right" or "near", "near", which is independent of reference frames, is usually chosen (Mainwaring et al., 2003)[10].

5 Conclusions

In summary, our preliminary results demonstrate the effects of indeterminate spatial descriptions. When individuals interpret such descriptions, they have distinct preferences for certain sorts of spatial models. If they then encounter an assertion that is inconsistent with this model, though not with the discourse itself, then they have difficulty in finding a consistent interpretation. In other words, the need to consider multiple possibilities creates a special difficulty if individuals' preferences bias them toward a model of the wrong possibility. Indeterminacy usually increases difficulty in deductive reasoning, because individuals need to represent multiple possibilities. As we have shown, support for detecting and efficiently representing indeterminacy can effectively reduce indeterminacy effects that usually impair human deductive reasoning.

The reported results have also implications for cognitive ergonomics. Systems supporting users in schematic spatial reasoning should anticipate model preferences, which may be culturally determined. As has been shown, the order of presentation affects how humans integrate information. Furthermore, humans can handle indeterminacies better if they are represented in an obvious and familiar way. One- or two-dimensional diagrams may induce suboptimal mental representations even if those layouts are the explicit task content. Users should be supported in detecting indeterminacy and, if possible, also in representing indeterminacy.

Acknowledgements

This research was supported by grants from the Deutsche Forschungsgemeinschaft (DFG) within the Transregional Collaborative Research Center SFB / TR 8 Spatial Cognition (www.sfbtr8.uni-bremen.de) to Markus Knauff, and by an NSF grant (BCS-0076287) to Johnson-Laird to study strategies in reasoning. Markus Knauff is also supported by a Heisenberg Award from the DFG.

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