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Abstract

In an eye tracking experiment, the interplay of visual and verbal information was studied in the domain of spatial relational reasoning. Standard verbal two-dimensional reasoning problems were presented auditorily along with visible context. In one condition, the visual-verbal interplay was designed to limit the number of interpretations that participants should consider for a set of premises. Past research has shown that visual context does not appear to limit the number of interpretations participants produce in this domain. In the present study, however, participants' responses, premise processing times, and gaze behavior confirmed that the interplay of visual and verbal information successfully directed participants towards a single interpretation when functional constraints disambiguated spatial relations. The results corroborate theories of situated language processing and demonstrate perceptual grounding and functional modulation in spatial reasoning.

Keywords: Spatial relational reasoning; visual-verbal integration; mental models.

Situated Language Comprehension

Comprehending language that refers to visible context involves rapid and even predictive shifts of attention towards likely referents in a visible scene. In situated language comprehension, perceptual and linguistic processing are closely intertwined (Altmann & Kamide, 1999; Knoeferle & Crocker, 2006). For example, perceptual-linguistic integration has been shown to quickly disambiguate syntactic structure, referents of noun phrases, and the interpretation of verbs. In spatial language, semantic uncertainty concerns locations and spatial relations. For example, "right of" often denotes a region rather than a specific location. Multiple additional constraints can take effect in spatial language processing to sharpen the interpretation of spatial descriptions. This includes the visible context as well as functional constraints (Coventry & Garrod, 2004).

Whereas the interplay of perceptual, linguistic, and semantic processing has been studied extensively for the comprehension of single utterances including statements of spatial relations, there have been few attempts to demonstrate its effect on reasoning with spatial premises. Spatial relational reasoning problems vary in difficulty depending on the number of possible interpretations of a set of premises. Visible context and functional constraints should take effect in the interpretation of extended spatial descriptions in reasoning problems as in the comprehension of single utterances. In this paper we demonstrate that visible and functional constraints mesh together on-line with verbal information to limit the number of interpretations considered by participants to solve spatial reasoning problems.

Spatial Relational Reasoning

In experiments on spatial relational reasoning, reasoners are asked to infer or evaluate spatial relations based on several stated spatial relations. For example: *The apple is to the left of the banana, the carrot is to the right of the banana. Where is the apple with respect to the carrot?* The spatial array or spatial mental model that satisfies the relations stated in the example is:

A(pple) B(anana) C(arrot)

The model yields the relation that holds between the apple and the carrot and thus the sought inference: *The apple is to the left of the carrot.* Such one-dimensional three-term series problems have been studied extensively with spatial and non-spatial relations (e.g., *better* and *worse*). Two-dimensional problems (Byrne & Johnson-Laird, 1989) have become standard tasks for studying spatial relational reasoning as well. Such problems are used here embedded in the context of planning seating arrangements for guests at tables.

Table 1 shows three types of two-dimensional problems, which differ with regard to the number of alternative seating arrangements fulfilling the set of spatial premises. One arrangement is possible for one-model problems. Two arrangements are possible for the two-model problems, in which the second premise introduces this indeterminacy.

In determinate two-model problems, the spatial relation between the guests in the bottom row (D and E) is the same in both possible arrangements (D sits to the left of E), whereas this relation differs between the arrangements for indeterminate two-model problems. Thus, the correct

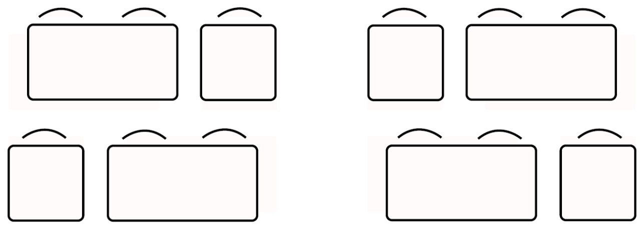

Figure 1: The two table arrangements

answer for indeterminate two-model models is "both are possible". When participants are presented with these three types of problems and are asked to indicate or evaluate the spatial relation between D and E, their accuracy is reliably higher for one-model and two-model determinate problems than for two-model indeterminate problems (Byrne and Johnson-Laird, 1989). The difficulty of two-model indeterminate problems conforms with model theory's prediction that accuracy should decrease if multiple mental models have to be considered to solve a reasoning problem (Johnson-Laird & Byrne, 1991).

Spatial Reasoning with Visible Functional Context

In an earlier study with two-model problems (Coventry, Venn, & Armstead, 2002), functional relations between familiar objects (e.g., cup on saucer) did not constrain interpretations, possibly, because participants did not regard functional relations as relevant to the reasoning task. Guided by these prior findings, we designed a novel task with stronger functional constraints. The physical context consisted of the table arrangements shown in Figure 1.

Table 1: Examples of reasoning problems

Problem Type	Premises and Response Alternatives	Possible Interpretations	
One Model Problem			
	<C prefers to sit alone> A sits to the left of B C sits to the right of B D sits in front of B. E sits in front of C 1) D sits to the left of E (correct) 2) E sits to the left of D 3) both are possible	**A B C** **_ D E**	
Determinate Two-model Problem			
	<C prefers to sit alone> A sits to the left of B C sits to the right of A D sits in front of A E sits in front of C 1) D sits to the left of E (correct) 2) E sits to the left of D 3) both are possible	**A B C** **D _ E**	A C B D E _
Indeterminate Two-model Problem			
	<C prefers to sit alone> A sits to the left of B C sits to the right of A D sits in front of B E sits in front of C 1) D sits to the left of E (implied) 2) E sits to the left of D 3) both are possible	**A B C** **_ D E**	A C B _ E D

Note. Participants were presented auditorily with the assertions of a problem while seeing a schematic table arrangement on the screen and then selected one of the three response alternatives to indicate the relationship between D and E. The listed problems were presented together with the left table arrangement shown in Figure 1. The assertion shown in bold face (<C prefers to sit alone>) was only presented in the one-model-implied condition. Models of seating arrangements that satisfy the <additional information> are indicated in bold face.

Consider the left table arrangement in Figure 1 together with the problems in Table 1. The sentence indicated in bold that states a seating preference of one individual (*C prefers to sit alone*) extends the standard problems. Without this additional sentence, participants should behave as in earlier studies with the standard problems and the table arrangement should remain inert. With the additional sentence, however, the visible table array should become relevant. Only a single table affords sitting alone and thus, the stated seating preference creates a functional constraint. We predicted that the array co-present during reasoning *in combination* with the stated seating preference should direct participants towards the single seating arrangement satisfying the preference (indicated in bold face in Table 1). We recorded participants' eye movements while they worked through problems in two conditions: the control condition (*neutral*) without the additional sentence stating a seating preference and the experimental condition with the additional sentence (*one-model-implied*).

Method

Participants. Twenty-four students of the University of Greifswald served as paid participants. The mean age of the 15 women and 9 men was 23.6 (*SD* 3.1).

Materials. Examples of *one-model*, *two-model determinate*, and *two-model indeterminate* problems are shown in Table 1. Each problem was paired with a fixed layout of tables. Two layouts of tables were used (see Figure 1). The location of the single table in the back row was important, because it should interact with the seating preferences stated in one-model-implied problems. We constructed four problems of each type for each condition (24 problems in total). The German sentence materials were digitally recorded spoken by a female voice.

We prepared instructional videos, in which a female who introduced herself as a restaurant manager motivated the experimental task as an exercise in planning seating arrangements. The restaurant manager explained with toy tables and chairs that participants should start with seating individuals in the back row and that *left of* and *right of* mean left of and right of from the participants' perspective. Finally, she explained the alternative responses to choose from. In the instructional video for the one-model-implied condition, the restaurant manager mentioned that sometimes guests are incompatible and should not be forced together.

The table arrangements subtended 21.0 by 16.4 degrees of visual angle and were shown on a 19" LCD monitor, below which the IR-camera unit of the 50Hz remote eye tracker (SMI RED) was mounted. Participants sat 70 cm in front of the monitor with the head on a chin rest, wore headphones and responded with keys on a standard keyboard.

Procedure. Participants were tested individually. After they had watched the instructional video, they completed two training problems and the 12 experimental problems for one condition. Then, after a short break, they watched the instructional video for the other condition, and again completed two training problems and the 12 experimental problems. The order of conditions was counterbalanced.

At the beginning of each trial, a table arrangement was shown and the introductory sentence (6.6 s) was presented auditorily. In the *one-model-implied* condition, after a 500 ms delay, the sentence identifying the individual who prefers to sit alone (1.8 s) was presented. Then, presentation of the first premise started after a delay of 1000 ms. In the *neutral* condition, the first premise was presented 500 ms after the introductory sentence. The presentation of the following premises was self-paced and triggered with the space key. Premises 1 and 2, each lasted 2.4 s, premises 3 and 4, each lasted 2.2 s. With a 500 ms delay after the fourth premise, the three response alternatives (e.g., *Darcey sits to the left of Ernest, Ernest sits to the left of Darcey, Both are possible*) were presented (9.0 s) in constant order. Participants chose one of the response alternatives with the number keys 1, 2, and 3. Responses were possible as soon as the presentation of response alternatives had started.

Results and Discussion

We first report response frequencies and response accuracy. In addition, we report processing times for the second premise, which distinguished one-model and two-model problems, and finally, we discuss selected gaze data. Premise processing times were measured from the end of presentation until the participant triggered the next presentation. We eliminated outliers higher than 2.5 standard deviations above the mean for processing times (3.9%). The analysis of gaze behavior was restricted to trials with sufficient data quality (98% for 22 participants; two participants with few remaining trials were excluded).

Response frequencies. Response frequencies are shown in Table 2 and reflect the effect of the one-model-implied condition on indeterminate two-model problems. "Both are possible" responses were less frequent and the response alternative reflecting the implied single model was chosen more frequently than in the neutral condition (57 vs. 33, respectively), paired t-test of mean frequencies, $t(23) = 3.32$, $p < .01$, $d = 1.03$. In contrast, for both remaining problem types, the response distributions were similar.

In the neutral condition, the two determined response alternatives were chosen with approximately equal frequencies for indeterminate two-model problems (33 and 40). Note that these frequencies could reflect a preference for one of the two possible models. The first determined model results if the guests in premise 1 are kept together and the third guest mentioned in premise 2 is placed "outside". The second determined model results if the third guest is placed "inside" the initial pair. Outside placements avoid a revision of the initial pair, but disregard the pragmatic implicature to pair the guests in premise 2 (van der Henst, Chevallier, Schaeken, Mercier, & Noveck, 2008). The slight trend towards "inside" placements as opposed to a common "outside" preference in the neutral standard task is probably the result of the presented table arrangement as explained in the section on fixation proportions below.

Table 2: Frequencies of responses, mean accuracy (with standard error), and mean processing times for the second premise (with standard error) for each problem type by condition (one-model-implied vs. neutral)

	Response					
Problem Type	Determined	Determined	Both possible	Total	Percent Correct	Processing Time 2^{nd} Premise (in msec)
One Model Implied						
One Model	54 (correct)	32	10	96	57.3 (5.7)	2900 (240)
Two Model Determinate	67 (correct)	24	5	96	69.8 (4.5)	3254 (296)
Two Model Indeterminate	57 (implied)	33	6	96	(not applicable)	3212 (255)
Neutral						
One Model	57 (correct)	33	6	96	59.4 (5.2)	3946 (437)
Two Model Determinate	60 (correct)	27	9	96	62.5 (5.2)	5568 (586)
Two Model Indeterminate	33	40	23 (correct)	96	26.0 (5.1)	6339 (698)

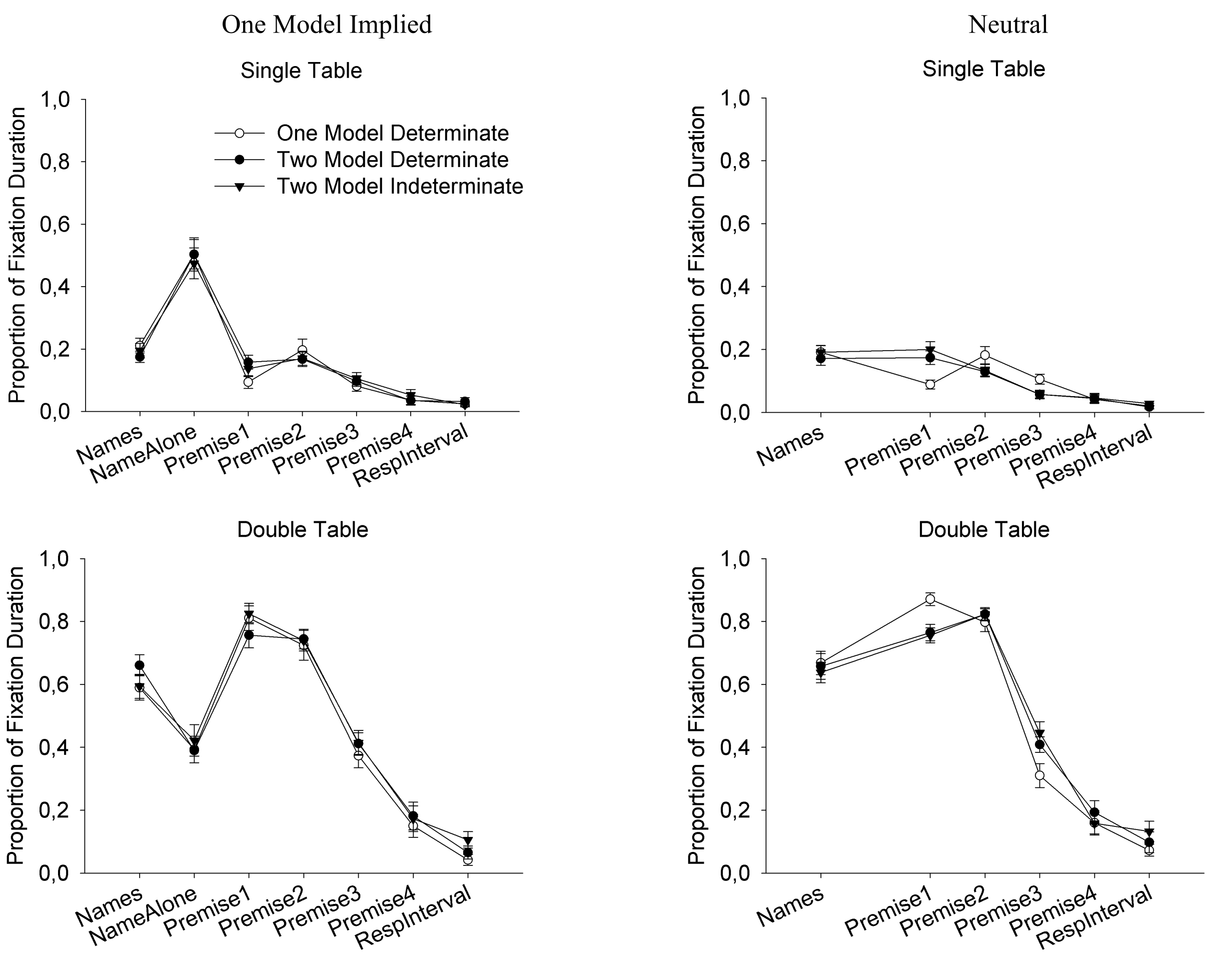

Figure 2: Mean proportions of fixations on the single table in the top row (shown in the top row) and on the double table in the top row (shown in the bottom row) for the sequential intervals within a trial separately for the one-model-implied condition (left column) and the neutral condition (right column) and for problem types; error bars indicate the standard error.

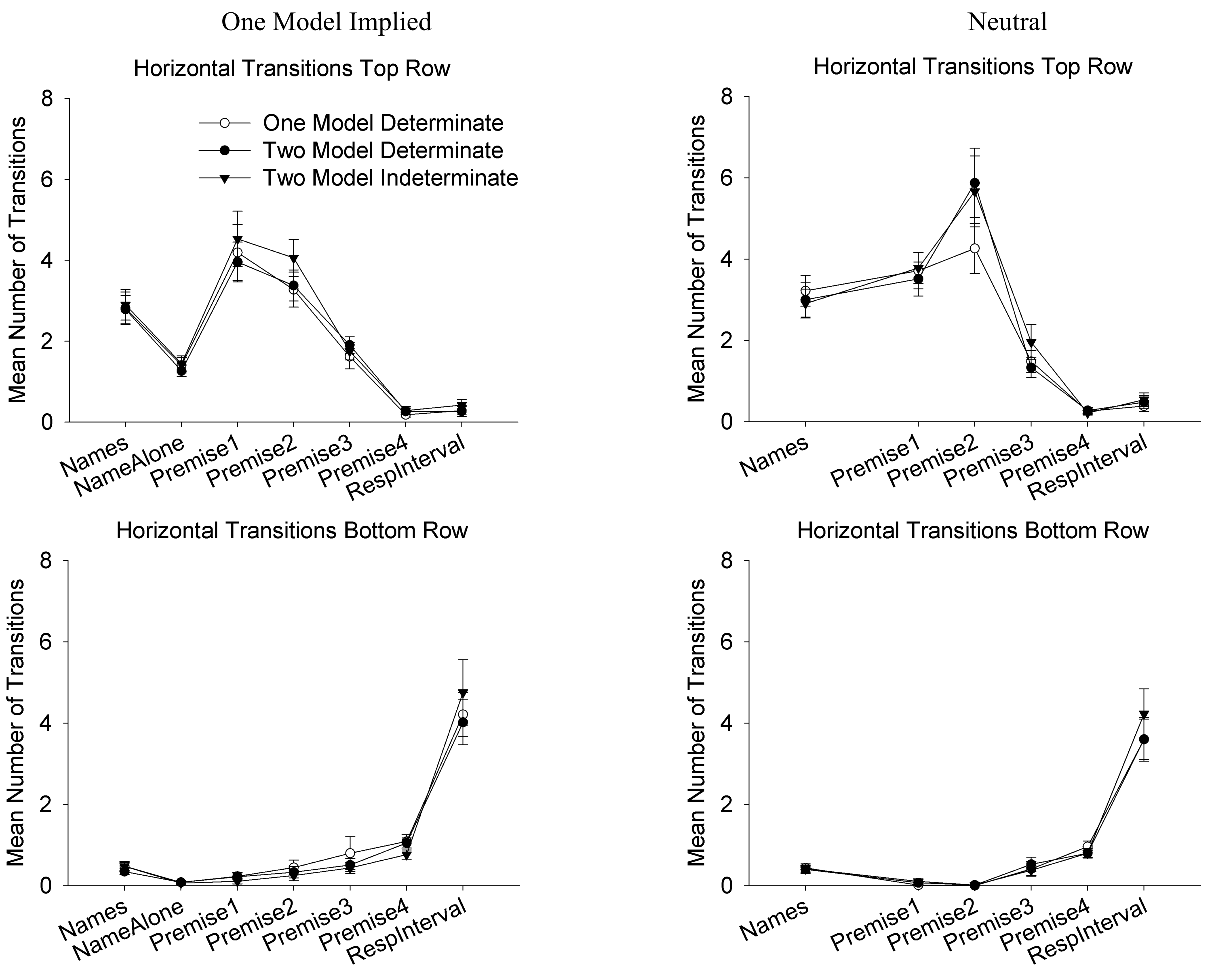

Figure 3: Mean number of horizontal transitions between seats in the top row (shown in the top row) and in the bottom row separately for the one-model-implied condition (left column) and the neutral condition (right column) and for the problem types; error bars indicate the standard error

Response accuracy. Mean percentages of correct responses are shown in Table 2. In both conditions, accuracy was slightly, but not significantly higher for two-model determinate problems than for one-model problems. In the neutral condition, accuracy for indeterminate two-model problems was significantly lower than for determinate two-model problems, paired t-test, $t(23) = 5.29$, $p < .001$, $d = 1.44$. This difference is consistent with the typical accuracypattern in the standard task. Furthermore, the low accuracy of 26 % correct for neutral indeterminate two-model problems is common if premises are presented auditorily (van der Henst et al., 2008).

Premise processing times. Mean processing times after the second premise are shown in Table 2. Elevated processing times for two-model problems suggest that participants considered multiple interpretations because the second premise introduced ambiguity in two-model problems. Only in the neutral condition, mean processing times were significantly higher for two-model problems than for one-model problems. This interaction was confirmed in an overall 2 x 3 repeated-measures ANOVA, $F(2, 46) = 6.67$, $p < .01$. The main effect of condition, $F(1, 23) = 22.34$, $p < .001$, and the main effect of problem type, $F(2, 46) = 13.88$, $p < .001$, were also significant. Separate one-way repeated-measures ANOVAs confirmed the effect of problem type in the neutral condition, $F(2, 46) = 11.10$, $p < .001$, but not in the one-model-implied condition, $F(2, 46) = 2.01$, $p = .15$.

Fixation proportions for the top row of tables. Figure 2 shows proportions of fixations measured from the start of a sentence to the start of the next sentence. In the one-model-implied condition after the introduction of the guests to be seated (*Names*), an additional sentence indicated the guest who "prefers to sit alone" (*NameAlone*). The presentation of this sentence triggered fixations of the single table in the top row, at which this guest had to be seated to meet the stated preference.

During processing of premises 1 and 2, fixation proportions indicate that attention was allocated mainly at the double table, and they hardly differed between problem types. For one-model problems in the neutral condition, however, premise 1 directed less gazes to the single table and more gazes to the double table. This probably reflects a subtle interaction of the table arrangement in the top row with the wording of premise 1: In all four one-model problems, left-of in premise 1 was combined with a left double table and right-of with a right double table. In half of the two-model problems, however, left-of in premise 1 was combined with a single table on the left and right-of with a single table on the right, which presumably prompted seating the subject of premise 1 at the single table. This effect of the combination of spatial relational terms and table arrangement was absent in the one-model-implied condition. There, the functional constraint biased against seating guests mentioned in premise 1 at the single table because those mentioned in premise 1 never were the dedicated singles. Hence, fixations after premise 1 were directed to the double table irrespective of problem type.

After premise 2, fixation proportions for the top row decreased. Only for the top double table in the neutral condition, they were slightly higher for two-model problems suggesting the consideration of alternative arrangements.

Horizontal transitions. Mean numbers of horizontal transitions between tables in the top and bottom rows are plotted in Figure 3. Note that premises 1 and 2 were identical for determinate and indeterminate two-model problems. Thus, all differences between determinate and indeterminate two-model problems up to premise 2 reflect error variance. In the neutral condition but not in the one-model-implied condition, horizontal transitions in the top row were more frequent for two-model problems, paired t-test, $t(21) = 2.49$, $p < .05$, $d = 0.43$. This result confirms the conclusion drawn from premise 2 processing times: In the neutral but not in the one-model-implied condition, participants sometimes considered alternative seating arrangements for the top row. This additional processing took time and was accompanied by fixations and transitions within the top row.

Horizontal transitions in the bottom row rarely occurred before the response interval. The following steep increase while considering the response suggests that participants actually placed and processed spatial indices corresponding to the two guests mentioned in premises 3 and 4 within the bottom row of the visible table arrangement instead of, for example, just considering spatial relations of the associated guests in the top row.

Selected fixation proportions for the bottom row. Finally, we focus on fixation data for a single seat to infer the interpretations considered in reasoning. As visible in Table 1, the middle seat in the bottom row remains free in one of the two possible models for the determinate two-model problem. This was true for all four determinate two-model problems. The model with the free middle seat is always the one that meets the seating preference in the one-model-implied condition. Thus, a reduced fixation proportion for this seat affords direct evidence that participants considered predominantly this model in the one-model-implied condition. We computed the respective fixation proportion for the interval from the onset of premise 3 until the response for both conditions. As expected, the fixation proportion was lower in the one-model-implied condition than in the neutral condition (.35 vs. .44, respectively; *SD*s .15 and .14), paired t-test $t(21) = 2.47$, $p < .05$, $d = 0.63$.

Conclusions

As expected, participants considered predominantly the implied model in the one-model-implied condition and processed two-model problems as one-model problems. By employing strong functional constraints we succeeded in demonstrating the disambiguation of spatial relation terms in reasoning, which previously had failed with weaker functional constraints.

Eye-tracking proved valuable for providing direct evidence of situated language processing and perceptual grounding in a spatial reasoning task. Participants directed their attention to those locations on the visible arrangements where the verbally mentioned guests were explicitly seated. Moreover, they also directed their attention to the top single table as soon as the seating preference for this table was mentioned. Thus, it was not only spatial language that induced attention shifts, but immediate inferences from object affordances and functional constraints (Coventry & Garrod, 2004). This corroborates the coordinated interplay account (Knoeferle & Crocker, 2004) and similar theories of situated language processing.

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