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Incremental Model Construction: Eye-movements reflect mental representations and operations – even if there is nothing to look at.

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Abstract

In the following we present a cognitive model and a visual world experiment to test a fundamental hypothesis derived from the mental model approach: the assumption that special relational reasoning relies on a mental model manipulation device responsible for model construction, inspection and variation. We will provide evidence for a direct linking hypothesis of eye-movements, demonstrating that the eye reflects the fundamental operations of model construction, even if there are no objects to look at.

Keywords: Spatial reasoning; eye-movement study; preferred mental models; visual world experiment; attention focus

Introduction

There are a number of different cognitive theories which try to explain the human reasoning process. Proponents of theories based on *formal rules* (Braine & O'Brien, 1998; Rips, 1994) claim that people solve reasoning problems by applying formal rules (e.g. transitivity rules) to abstract representations of the premises. In contrast, proponents of *mental models* claim that the main strategy employed in reasoning is the successive construction of a so-called mental model of the state of the affairs. This model contains all the information given in the premises. New information, such as a reasoning problem's conclusion, is generated or evaluated by inspecting possible models (Johnson-Laird & Byrne, 1991). To provide an example:

(1) The plate is to the left of the knife.
The fork is to the left of the knife.
The glass is in front of the knife.
The spoon is in front of the plate.

This describes the following two possible models:

	spoon	glass	spoon		glass
fork	plate	knife	plate	fork	knife

The structure of such tasks is typically identical in everyday life and in psychological laboratories: there is always some given spatial information (the so-called *premises*) and the participants have to generate a (putative) conclusion based on these premises. The premise information can be discerned by small-scale spatial objects (e.g. fruit or cutlery which have to be arranged) or large-scale objects (e.g. prominent buildings such as church towers). In the domain of reasoning with spatial relations, the theory of mental models (MMT) has received substantial empirical support (Byrne & Johnson, Laird, 1989; Johnson-Laird & Byrne, 1991; Jahn, Knauff, Johnson-Laird, 2007; Ragni, 2008). MMT assumes a three stage process consisting of a comprehension, a description, and a validation phase. In the *comprehension phase*, reasoners construct a mental model that reflects the information from the premises. If new information is encountered during the reading of the premises it is immediately used in the construction of the model. During the *description phase*, this model is inspected to find new information that is not explicitly given in the premises. Finally, in the *validation phase* the reasoner tries to construct alternative models that refute this putative conclusion. However, some questions remain open with regards to how people deal with multi-model problems. For example, which model is constructed first, and does this model construction adhere to certain principles? Why do reasoners neglect some models?

The preferred mental model theory (PMMT) claims that humans generally tend to construct a preferred mental model (PMM). The PMM is the starting point for deriving a putative conclusion. In the model variation phase the participants tend to make local and continuous transformations starting from the PMM to search counter-examples (Rauh et al., 2005).

Several predictions of the PMMT about insertion principles as well as transformation strategies in spatial relational reasoning can be shown (Ragni et al., 2006). For the second premise in example 1 "the fork is to the left of the knife" there are two possible arrangements. Humans typically tend to process these premises sequentially, i.e. first, a mental model of "plate - knife" is generated and then the new information, the fork, is inserted into the existing model. The second premise allows the insertion of the fork at two different places: inbetween the plate and the knife (**f**irst **f**it principle), or to the left of the plate (**f**irst **f**ree **f**it principle). It had been shown empirically that PMMs are generally constructed by using the *fff*-principle (Ragni et al., 2006). One very important point, however, is: is it possible to decide the classic question about the way we reason based on evidence from eye-movements? MMT has a necessary assumption–that mental models are constructed incrementally and therefore use a mental model manipulation device. Is it possible to demonstrate model construction and manipulation operations in eye movement data?

In this paper, we first work out the central questions important for such an eye-movement study in spatial relational reasoning. We will then present an experiment we have conducted to investigate a possible linkage between eye-movement and mental model operations. We will argue that eye-movements reflect operations on mental models, even in the absence of relevant visual information.

State-of-the-Art

Reasoning with spatial relations is certainly one of the most thoroughly investigated parts in the field of deductive reasoning (Byrne & Johnson-Laird, 1989; Johnson-Laird & Byrne 1991; Goodwin & Johnson-Laird, 2005; Ragni, 2008). In recent years only a small number of researchers have investigated human deductive reasoning by using eye tracking studies. Abed (1991), showed that left-to-right readers (Western subjects) had the highest number of left-to-right eye movements when they observed visual stimuli, while right-to-left readers (Middle Eastern participants) had the highest number of right-to-left movements. This set of studies suggests that reading habits strongly influence scanning direction.

Körner & Gilchrist (2004) analyzed how participants process a question about the spatial relationship between two letters while looking at a visualization of this scenario containing the two letters and two others as distractor items. The study shows that the format of the question influenced the nature of the eye movements. Furthermore, a tendency to use additional eye movements to generate a fixation sequence corresponding to the order of the letters in the question was identified.

The construction or retrieval of a spatial mental model showed similar eye movements which were used to coordinate elements of the internal model with elements of the external world (Spivey & Geng, 2001). This supports the idea that the scan path plays a role in structuring visual information to facilitate reasoning.

While there is, to our knowledge, no pure relational reasoning research covering indeterminate tasks using eye-tracking techniques up to this day, there is some work about conditional reasoning. One of the very first works concerning reasoning investigated the Wason Selection Task (Ball et al., 2006). This research revealed an imbalance in inspection time between selected and rejected cards observed with indicative selection tasks and a generalization to deontic versions of the task. This inspection time has been connected to the heuristic-analytic account (Evans, 1983) of the selection task, where implicit heuristic processes direct attention to relevant aspects of the problem and determine card selections.

Johansson et al. (2006) have investigated the question of how eye movements correlate with and reflect the positions of objects while participants listen to a spoken description. Nevertheless, there is an ongoing debate as to whether eye movements reflect the search of a spatial mental model as an internal representation of a picture, imagery (Finke, 1989, Kosslyn, 1994), a mental model (Johnson-Laird, 1983), or if no internal image exists and the eye movements only indicate that the external environment will be used as pointers or indexes (Pylyshyn, 2002; Spivey & Geng, 2001) which propose a rule-based approach.

The Hypothesis

In the SRM (Spatial Reasoning by Models, e.g. Ragni et al., 2007) a focus was used to place, manipulate objects and inspect a model to find spatial relations which are not explicitly given in the premises.

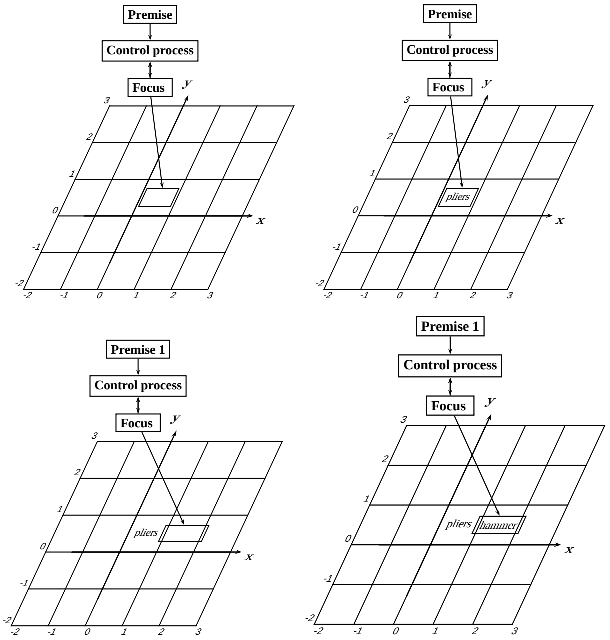

Figure 1: The SRM model (Ragni et al., 2005; Ragni & Knauff, 2008) after processing the first object of a premise of the form “the pliers is to the left of the hammer”.

We want to explore to what extend the focus manipulation device of the SRM shares similarities with the eye-movements of humans – even if there are no visual but only auditory stimuli. Previous findings (Ragni et al., 2007) on this focus manipulation device indicate that the number of operations based on the movement operations of a so-called focus is a good predictor of cognitive complexity. This SRM model allows for an identification and specification of mental model operations in spatial reasoning and consists of an input device, an array, a focus, and is controlled by a control process (Fig. 1.). The focus (manipulation device) is able to move right/left/front/ and behind, can insert and delete objects, and write annotations (indeterminacy). Certainly the main theoretical point is that it allows the introduction of a formal complexity measure to explain human reasoning difficulty. Our starting point is that this theoretical assumption may have a counterpart in eye-movements. We explore this question by recording eye movements during the processing of spatial relational reasoning problems.

The Empirical Investigation

If the eyes follow mental operations, they may do so even if limited visual information is provided. We conducted an eye movement study where only the first mentioned object was presented in the center of the screen, where it remained throughout the whole trial. All other objects mentioned in the spoken premises were not displayed.

Eye movements are linked mostly to automatic bottom-up processes. The main question of this experiment is if eye-movements may reflect bottom-up mental operations if one deals with relational reasoning tasks. In addition to the object in the center, we presented a two-dimensional low-contrast grid covering the entire display (Figure 1). If participants move their eyes according to the mental construction operations, they might use the grid for aligning their fixations, however, we have not encouraged or instructed the participants to do so. Otherwise, data analysis would have to be much less accurate, since saccades and fixations would probably be much too noisy and chaotic between participants to be analyzed together.

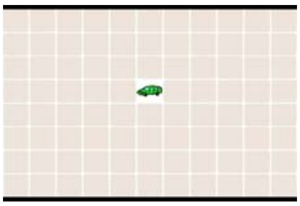

Figure 2: The presented screen in our eye movement study.

Only the first mentioned object (in this case the green car) of the premises was visible during the whole premise presentation (i.e. no other visual stimulus appeared).

We used four premises with five objects (5-term series problems). The premises have eight different construction sequences for the insertion of the next object (combination of insertion direction left or right) as well as determinate and indeterminate problems. Objects were always introduced in the order *new object in relation to the known object*.

Table 1: Determinate problems.

EXAMPLE: ***Determinate Problem***	
Premises	***Model***
A is to the left of B	A B
C is to the right of B	A B C
D is to the right of C	A B C D
E is to the right of D	A B C D E
Question	
Example: Which relation has B to E (A to D)?	

Table 2: Indeterminate problems

EXAMPLE: ***Indeterminate problem***				
Premises	***Preferred M.***	***Alternative Models***		
	1	**2**	**3**	**4**
A is to the left of B	AB	AB	AB	AB
C is to the left of B	CAB	ACB	ACB	ACB
D is to the left of C	DCAB	DACB	ADCB	ADCB
E is to the left of D	EDCAB	EDACB	EADCB	AEDCB
Question				
Example: Which relation has C to E (E to C)?				

A question about the relation of two objects in the model provides the information if the participants have built a possible (indeterminate) or correct (determinate) model. The four premises were presented one after the other acoustically. Each premise will be presented in a determined time (externally paced). At the end the participant were asked to decide which relation holds between two objects and to press the button for "left" or "right", respectively. During the entire trial, they see a grid with 11 x 8 squares on the screen and only the first object was placed in the center square as an anchor. Only eye-movement data from correct answers were analyzed.

We calculated the proportion of fixations on each of the nine interest areas (IAs) per time bin (500 msec) during the presentation of the premises. The underlying grid (11 x 8 squares) provided the interest areas (IAs). However, since only one-dimensional horizontal models were investigated, we limited the analysis to the four left (IA1-4) and four right squares (IA6-9) in one line, plus the center itself, where the first object was presented (IA 5). Since half of the trials were mirror images of the other half, we mapped those trials onto the other by mirroring the IAs.

Hypotheses

1) *Is there a correspondence of eye-movements and the mental focus in the SRM for determinate tasks?* As there is only one possible model in determinate tasks, there is only one possible movement of the mental focus – from the given object, which was already introduced in the premise before in the relational direction to the insertion of the new object in the present premise.
2) *Do the eye-movements reveal a preferred mental model insertion principle during indeterminate tasks?* We assume that the *insertion principle "free first fit"* (see above) will also be observable during the indeterminate problems. For this reason, we expected increased fixation proportions on the first free place compared to the first place that fits.
3) *Do the eye-movements explain the figural effect?* A strong effect of reasoning complexity is the so-called figural effect, i.e. the difference between continuous insertions or discontinuous insertions (Knauff et al., 1998). This can be explained by the direction change

of the mental focus (cf. Fig. 1). If there is a correspondence between mental focus and eye-movements there should be an analogous change of the IA fixations. If changes of the direction are necessary the IAs during the “way” to the opposite end of the model should be more frequently fixated and there should be a higher duration until the target IA is reached.

Participants. Eighteen undergraduate students of the University of Freiburg took part in this experiment. They were paid for their participation.

Materials. The experimental stimuli contained 32 problems, 16 determinate and 16 indeterminate problems (see Tab. 1 & 2). Examples of deterministic tasks are the following:

(2) A is to the left of B
C is to the right of B
D is to the right of C
E is to the right of D

(3) A is to the left of B
C is to the left of A
D is to the left of C
E is to the left of D

Which relation holds between B and D?

While the determinate task (2) constructs the model only in one direction (and is therefore encoded in the following by RRRR, since each new object is inserted to the right of the previous one) the determinate task (3) has a direction change, after the first premise (and is therefore encoded as RLLL). An example for an indeterminate task (RRRR) is

(4) A is to the left of B
C is to the right of A
D is to the right of C
E is to the right of D

Which relation holds between C and E?

Procedure & Design
We conducted an eyetracking experiment (using SR Research Experimental Builder and an EyeLink II system) in order to measure reaction time and accuracy as well as the eye-movements during the reasoning tasks. All 32 (determinate and indeterminate) tasks were presented in a randomized order. Each of the four premises was presented auditorily. Only the first object was presented during the whole task (cp. Figure 1). After the last premise two objects were offered and the relation between them had to be drawn by pressing one of the answer keys (left or right).

Results
This experiment provided some intriguing results – due to the space limitation we can present only a subset of the most remarkable ones.
Determinate models. Our first hypothesis assumes that in determinate cases the eye-movements of the participants correspond to the mental focus movements in the SRM. If this is the case, then the eye-movements for tasks of the form LLLL should go directly in one direction, while for tasks with direction changes (e.g. LRRR) the fixation proportions should be increased on the IAs corresponding to the directions change. The results for the first case are depicted in Figure 3, the result for the latter in Figure 5. Here the eye-movements correspond strongly with a successive model generation, i.e. each corresponding cell is fixated exactly after the respective object is named.

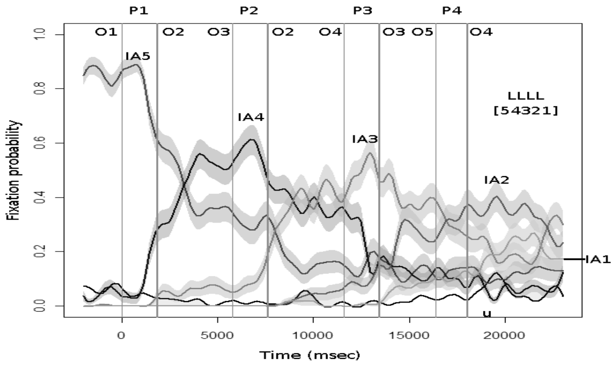

Figure 3. The determinate task consists of 4 premises (P1 to P4) with the relations left (LLLL). The number in the bracket denotes the IAs which should be fixated successively according to the prediction. The vertical partitions (e.g. O1, O2, etc.) represent the onset for the acoustical presentation of the respective object. The different lines represent the fixation probabilities of the different interest areas (IA). The standard error of the mean is represented by the transparent area above/below each line.

Indeterminate models. In contrast to the determinate case the eye movement pattern changes in indeterminate cases (cf. Figure 4): For instance, analyzing again the case LLLL, the indeterminacy occurs during the presentation of the second premise, where the position of the third object allows for several positions.

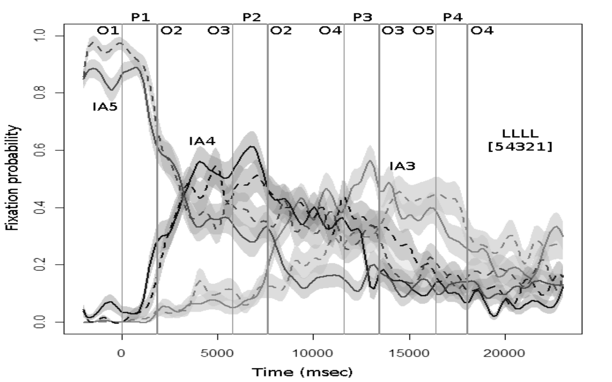

Figure 4. The results for the determinate and indeterminate problems with 3 IAs (LLLL). The continuous lines represent the determinate case while the dashed lines represent the

indeterminate case (cp. Fig. 3). In the indeterminate case this is inserted later (cp. IA 3 in Figure 4) than in determinate cases. Second, the interest area 5 (with the visual stimulus) is longer, later and even (together with IA 4) more frequently inspected than in the determinate case. Third, IA 3 is later fixated but reaches the full attention during the third premise where Obj 4 (has to be inserted left to Obj 3). This shows that Obj 3 is inserted in IA 3 (at the next free position), i.e. the fff-principle is used and not inbetween IA4 and IA5, which would correspond to the ff-principle.

The figural effect. The third hypothesis is about the figural effect – do fixations show a clearer pattern when premises are presented in a continuous or discontinuous order? Here we have found strong differences (especially with IA 4) in the classical case between the direction changes and the interest areas between LLLL and LLRR (Fig. 5) and LRRR (Fig. 6).

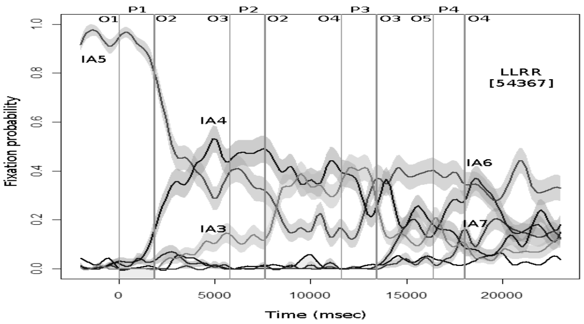

Figure 5. The results for those determinate tasks with exactly two direction changes (LLRR). (cp Figure 3).

As expected, the error rates differed significantly between determinate and indeterminate tasks (Wilcoxon-Test, Z=-2.291, p <0,022), but there were no differences between verification times (Wilcoxon-Test, Z=-0,631, p =0,528).

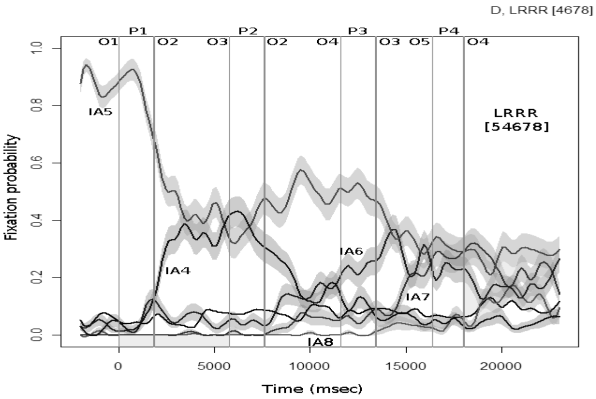

Figure 6. The results for those determinate tasks with one direction change in the second premise (LRRR or RLLL) (cp. Figure 3).

General Discussion

The theoretical assumption of a mental model manipulation device (the so-called focus) which explains a number of empirical findings (Ragni, 2008) concerning cognitive complexity (figural effect, premise order effect, relational complexity (Goodwin & Johnson-Laird, 2008)) could be supported by our eye tracking experiment.

Eye-movements of reasoners reflect the mental representations and operations even if four of the five objects were not visually presented on the screen and even if the participants had not been encouraged or instructed to do so. The data leads to the following five results: first, in *determinate cases* without direction change the successive construction of the model reflected by the corresponding eye-movements could be identified. Second, if direction changes were necessary the proportions of the intermediate IAs would be raised. In comparison to one-way model constructions more fixations in different IAs are necessary which increase the time until the target IA would be fixated. This corresponds to the figural effect (Knauff et al., 1998) and offers an explanation for the different complexities. Third, Fig. 4 depicts the latency during the introduction of an *indeterminate premise* which could also be found in self paced reasoning problems (Ragni et al., 2007). Fourth, by means of the eyetracking experiment we were able to identify preferred mental models. Although object insertion principles like first fit are possible the results show a clear preference for the first free fit principle (corresponding to IA3, see Fig. 4) in which fixation probability increased whereas the competing principle (corresponding to IA4, see Fig. 4) decreased. Fifth, this is remarkable evidence for a top-down mechanism of eye-movement control in the absence of reliable bottom-up information (e.g. Spivey & Geng, 2001).

There are some potential issues with our conclusions. The visible grid-structure might have supported or even triggered eye movements. Even if this was the case, Fixations corresponded beautifully to the mental model operations (especially the preferred mental model), and the grid did not provide any information about currently processed model. Furthermore, Johansson et al. (2006) demonstrated that there can still be eye movements even without a grid structure and also in complete darkness. One might argue that the eye movements were directly triggered by the named relations. As we cannot rule this out as a possibility for all determinate cases where the relation right is used (C is right of B) it does not hold for the first relation (which is always of the form “A is left (or right) of B”). During the first premise the eye movements are not in congruence with the named relation. If reasoning problems are processed in line with the mental model theory or the rule-based approach cannot finally be explained with this study, but the data from different laboratories suggests that the mental model theory can better explain the results which were found by means of behavioral, eye tracking and imaging methods for spatial relational reasoning problems.

Taken together, the data support fundamental assumptions of MMT, namely that mental models are built incrementally, successively used and refined for representing spatial information.

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