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Journal
Proceedings of the Annual Meeting of the Cognitive Science Society, 36(36)

ISSN
1069-7977

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Publication Date
2014

Peer reviewed

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Abstract

We study analogical reasoning in adults using an eye tracking methodology. In previous experiments, we studied the time course of analogy-making, looking at proportion of looking times and transitions. The main purpose of the present experiment is to test whether adults would adapt their search strategies to the difficulty of the analogical problems (Easy vs. Difficult problems). Difficult problems might have an impact on participants' visual strategies used by participants (Bethell-Fox et al., 1984) Looking-time durations and the number of key item-to-item transitions confirmed differences between the two conditions. We discuss the results in terms of conceptions of analogical reasoning.

Keywords: Analogical reasoning; eye tracking; strategies

Introduction

Analogical reasoning is a central feature of human cognition (Gentner & Holyoak, 1997; Holyoak, 2012). It involves the transfer of relations from a source domain to a target domain which is more or less distant. Analogical reasoning has been extensively studied from adult experimental, developmental and modeling perspectives and several general models have been proposed in order to characterize this form of reasoning in both children and adults (see French 2002; Gentner & Forbus, 2011, Holyoak, 2012, for reviews).

In the present paper, we will concentrate on the temporal organization of the search for a solution in adults, using eye tracking data. We will compare "Easy" trials with "Difficult" trials and study how participants adapt themselves to the constraint of these two types of problems. In eye tracking studies, it has been shown that the amount of attention paid to a particular item and the gaze-fixation are highly correlated (Deubel & Schneider, 1996; He & Kowler, 1992). There is a correlation between the fixation time associated with a given item and its informativeness (Nodine, Carmody, & Kundel, 1978). All of this argues in favor of using eye tracking technology to study analogy-making strategies.

Existing models of analogy make different predictions regarding *how and when* participants focus on and compare stimuli. Gentner and Forbus (2011) distinguish "align-first" models from "projection-first" models. Markman and Gentner (1993) propose an "alignment-first" conception in which one first aligns the stimuli that compose the base and the target domains. From the comparisons of local elements, of local and global structures from both sides, one derives which elements should be put into correspondence (e.g., Falkenhaimer, Forbus, & Gentner, 1989). In A:B::C:D paradigm, one would systematically compare the two pairs and would tend to align A with C and look for a D (or Ds) to be aligned with B.

By contrast, "projection-first" models (e.g., LISA, Hummel & Holyoak, 1997) begin by projecting information from the base pair (i.e., the A:B pair in the A:B::C:D paradigm) and, then, try to find matches corresponding to them in the target pair (i.e., the C:Ds). They predict more attention to the A:B pair and more A-B transitions first and, later in the trial, more attention to C and Target and more CTarget transitions, whereas alignment-first would be more consistent with a larger number of AC and BD transitions from the start of the trial.

Other resolution strategies which have features in common with the projection-first, alignment-first distinction have been described, such as the constructive matching versus eliminative matching distinction (Bethell-Fox, Lohman & Snow, 1984; Thibaut, 1991). In the constructive matching strategy, participants concentrate on the first part of the problem before studying the second part or the solution set, which is analogous to the projection-first. In the eliminative strategy, the source and the target are compared until the best option is selected in the solution set. This strategy makes no strong prediction on the time course of a trial since participants successive elimination could be done by projections or alignments. In any case, all these strategies rely on multiple, successive comparisons which must be coordinated.

Though valuable to decide between these different conceptions of information processing while reasoning, there are only a small number of eye tracking studies involving analogy-making (e.g., Bethell-Fox, 1982; Gordon & Moser, 2007; Thibaut et al., 2011). Gordon and Moser (2007) used scene analogies from Richland, Morrison and Holyoak (2006 ; Markman & Gentner, 1994) in which participants had to point which item in a scene had the same role as an item pointed to by the experimenter in the other scene (e.g. pointing to a boy chasing a girl, if the experimenter pointed to a dog chasing a cat). They found that adults initially focused on the "actor-patient" pair in the source image (i.e., a dog chasing a cat, which is analogous to our A and B terms) and then looked for the solution in the target image (a second actor-patient pair, e.g., a girl chasing a boy, analogous to our C and D terms). This is consistent with the constructive view or the projection-first conceptions (study A:B then C:D).

Bethell-Fox et al. (1984) used an A:B::C:D task, with easy and difficult *geometrical* analogies which had the same topography as our analogies (see below). They found that participants with less "fluid intelligence" relied more on the elimination of implausible answers, i.e. had more transitions within pictures in the solution set. Interestingly, difficult items elicited more saccades back to A and B, i.e., more time spent on the A:B pair of the problem before looking to alternatives. Participants also looked at the alternatives more often than in simple trials. The authors also found that when participants first looked at the correct answer, they later tended to look at a lower number of alternatives than when it was an incorrect answer that was first looked at. This is a clue of a constructive approach. If participants looked less at other options when their first look was for the correct answer, this means that they had already constructed a solution for the A:B pair which allowed them to recognize that the correct solution was correct.

Thibaut et al. (2011) conducted a developmental study with A:B::C:D semantic analogies and found key differences between adults and children in the temporal organization of their respective search profiles. First, adults focused on the A:B pair at the beginning of the trial, paying less or no attention to C and to stimuli in the solution set. Later they focused on C and the Target, which they compared with the semantically related distractor. At the end of the trial, the Target was their sole focus of attention. By contrast, children organized their search around C which they actively focused on during the entire trial. At the very beginning of the trial they paid more attention to C and B. They began looking at the Target and the semantic distractor earlier than in the adults' case. Thus, the main differences between children and adults were that children focused on C and B at the beginning of a trial, compared to A and B for adults. Also, the Target and the semantic distractor were focused on earlier by children than by adults. Results showed that children organized their search around C and paid less attention to A and B when necessary. Overall, adults behaved in a projection-first way (or constructive) whereas children followed neither a projection-first (or constructive) strategy nor an alignment-first strategy. They seemed to behave as if they organized their search around C.

Overall the available data suggest that adults are using the projection-first (constructive) strategy, i.e., more fixations at the actor-patient pair in the source image in scene analogies (Gordon & Moser, 2007), first fixations at the A:B pair, and AB transitions (Thibaut et al., 2011) and more fixations towards the A:B pair in difficult rather than in easy problems, or fewer saccades towards incorrect alternatives when the first saccade was towards the correct answer (Bethell-Fox et al., 1984).

Goals and Rationale

The objective of the present experiment was to test whether adults' strategies would be influenced by the difficulty of the analogy problems. We thus will use A:B::C:D semantic analogies with semantically related distractors and manipulate the difficulty of the problem.

Bethell-Fox et al. (1984) used perceptual analogies which were defined around a finite set of perceptual dimensions which were easy to identify. Their difficult trials were composed around more dimensions than easy trials. Distractors were more similar to the solution (e.g., one transformation) than in easy trials (e.g., two transformations). Hence, difficulty had to do with perceptual complexity in their study. As mentioned above, their results seem to indicate that their particpiants behaved according to the projection-first (constructive) strategy, starting with A-B rather than according to an alignment-first strategy (see Gentner & Forbus, 2011).

Here, we manipulate another type of difficulty in order to test its consequences on the strategy used by participants. Easy trials were trials in which the relation between A and B, and C and T was more obvious, according to a control group, than in difficult trials. An example of Easy trial is cow:milk::hen:? in which the solution, "egg", is straightforward. An example of difficult trials is violence:activity::gloom:? in which the relation between violence and activity (i.e., violence is a negative type of activity) is not obvious, and the solution ("mood") is difficult to find. Note that in Thibaut et al. (2011), adults only saw easy problems that could also be solved by 6-year-olds, but difficult trials are needed. Indeed, in terms of the search for a solution, difficulty is related to the semantic space that has to be explored. The general idea is that Difficult trials are defined around a much broader, more open space than Easy trials (see Thibaut et al. 2010b, for a discussion of the notion of semantic space and its role in analogies). Difficult trials should also elicit lower scores, more distractor errors, and longer reaction times than Easy trials.

Several hypotheses can be made regarding the time course of the trials in the different difficulty cases. *First*, difficult problems might elicit more alignments, either AC transitions or BT transitions, than Easy problems because participants would look more carefully at which stimuli are equivalent in the two pairs, because this correspondence would be more difficult to establish.

Second, it might also be the case that fixations towards A and B or AB transitions might be less dominant in the beginning of the trial because less obvious relations would elicit a more systematic exploration of the target pair and the solution set in order to find new solutions.

Third, Rattermann and Gentner (1998) proposed that object matches are processed before relational matches, even in the adult case. Gordon and Moser (2007) found no evidence of these object matches primacy in their eye tracking data: relational matches appeared before object matches (i.e., matches involving similar objects in both scenes such as two cats. By definition, these object matches were not relational matches). In our study, the analogous matches to the object matches used by Gordon and Moser were the semantic distractors. The Rattermann and

Gentner's (1998) view would predict that in Difficult trials, participants would have higher rates of transitions involving distractors (e.g., CSemantic distractors [CSemDis] transitions) at the beginning of the trial because the relational matches would not be straightforward. In general, this is because Difficult trials are less obvious and participants are considering more options in a more open semantic space, or first consider obvious associations such as C with distractors.

A *fourth* prediction is that participants might have to re-represent the A:B pair after seeing the solution set in Difficult trials more than in the Easy trials. This view would be compatible with higher rates of fixation on A and B, and of AB saccades in Difficult trials at the end of the trials than in Easy trials. In sum, Difficult trials might generate differences in the temporal organization of the search.

Methods

Participants

Participants were 20 students at the University of Burgundy (M=23.8 years; SD=4.2; from 17 to 35 years). They participated voluntarily and ignored the experiment rationale.

Materials

The task consisted in 22 trials (2 training trials and 20 test trials) of a verbal A:B::C:D task. The test trials were ten Difficult trials and ten Easy trials. The two training trials were displayed before the 20 test trials. The order of presentation of the test trials was random.

Each trial was composed of eight words written in black ink on a white background, corresponding to the A, B, and C terms of the analogical problems, and five potential solutions. The solution set was composed of the Target (T), two related-to-C distractors (SemDis), and two unrelated distractors (UnDis). Each word was presented in a black frame (220x220 pixels). The A, B and C terms were presented in a row at the top of the screen along with an empty black frame (for the picked up stimulus), and the 5 words composing the solution set were displayed in a row at the bottom of the screen (See Figure 1).

The trials difficulty was assessed by 12 university students. They were asked to solve the different problems and to evaluate the difficulty of the problem on a 1-7 scale. Difficult trials were rated significantly higher (M=3.9; SD=.4; range of 3.5 to 4.6) than Easy trials (M=1.2; SD=.1; from 1.1 to 1.3; two-sample related t-test: t(22)=23.2; p<.001; η^2_p=.961).

The task was presented on a Tobii T120 eye tracker (resolution: 1024x768) with an E-Prime (version 2.8.0.22) experiment embedded in a Tobii Studio (version 2.1.12) procedure to record participants' eye movements. Data were analyzed using a Statistica 8 software.

Procedure

Test sessions took place in an experimental room at the University of Burgundy. Each participant was tested individually.

After the eye tracker was calibrated, participants were tested in the analogical reasoning task. Participants were shown the eight words and were given the following instructions during the first training trial: "Here are two words [pointing to A and B]. They go together well. Can you see why these two [A and B] go together?" Once the participant had given a relation linking A and B, the experimenter confirmed it (if it was correct) or corrected it (in case of an irrelevant relation for the solution of the problem) and continued: "OK! Do you see this one [pointing to C]? What you have to do is to find in these five words [pointing to the solution set] the one that goes with this one [C] in the same way as this one [B] goes with this one [A]. So, if these two [A and B] go together because [giving the relation between A and B, which one goes with this one [C] in the same way?" When participants had given an answer, the experimenter asked them to justify their answer and gave a feedback. In case of an error and/or bad justification, the trial was explained in terms of the relations linking A and B on one side, and C and T on the other. Instruction and feedback were not given during test trials. Eye tracking data were recorded when the presentation of the problem started and stopped when an answer was given.

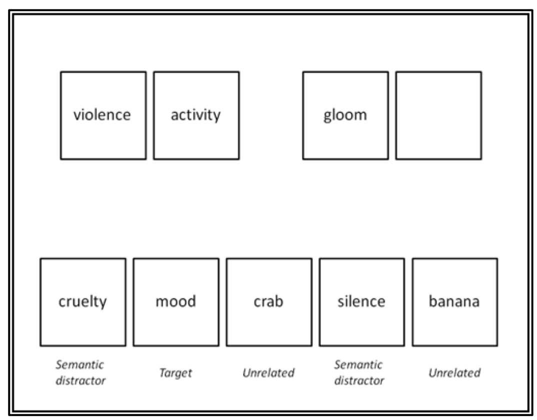

Figure 1: Example of the display used in the experiment.

Results

Before we come to the analysis of the time course of fixations towards objects and saccades (transitions) between object, we must first check that Difficult trials were more difficult than Easy trials. Data show that it was the case. Indeed, the mean rate of correct answers was significantly lower in Difficult than in Easy problems (t(19)=4.9; p<.001; η^2_p=.558)); all errors were semantic distractor choices. Difficult trials were also significantly slower than Easy trials (t(19)=9.92; p<.001; η^2_p=.838).

Eye Movement Analysis

We rejected trials in which more than 50% of the gaze time was not recorded. With this criterion, two trials were discarded from the data set. In the analyses, we used percentage of total looking times and of total number of saccades for comparisons.

In order to compare Easy and Difficult trials, we analyze the proportion of fixations and of transitions and focused on the distribution of key fixations and saccades in the trial (i.e., for example, fixations towards A or B fixations, or AB saccades, hereafter "transitions") which might differ in the two types of trial. To test our hypotheses, we divided all trials in three equal slices (i.e., 1/3 of the total length of the trial), in order to capture differences in the temporal dynamics of Easy and Difficult trials.

Fixations Among others we will be looking for the time course of fixations towards A and B, especially in the first slice. We will also focus on the difference between Difficult and Easy trials in each slice.

A three-way repeated measure ANOVA, with Type of Stimulus (A, B, C, T, SemDis, UnDis), Condition (Easy, Difficult) and Slice (first, middle, and last) as within-subject factors, was used to assess the temporal dynamics of rates of fixations on the distractors and the source domain (Figure 2).

The most *important result* was the significant interaction between the three factors ($F(8,152)=25.3$; $p<.001$; $\eta^2_p=.571$). Tukey HSD on individual slices revealed the following pattern. *Slice 1* had the same pattern for Difficult and Easy trials, that is higher rates of B than all the other stimulus types, of A than all the others, except B, of C than any item in the solution set. Thus, there were more gazes at the A:B pair, followed by C gazes. Comparison between Difficult and Easy trials showed, for Easy trials, significantly higher proportions of A, B fixations, and lower proportions of C and SemDis fixations and marginally significantly lower fixations for Target. This suggests that Difficult trials were recognized quite early as "not obvious" which led participants to start to explore the solution set earlier than in the Easy trial case, which is consistent with our second hypothesis. The high proportions of A and B fixations in both conditions confirms previous data showing that participants first analyze the A:B pair even though this is less pronounced in the Difficult condition.

For *Slice 2*, in Difficult problems, the only significant difference was between C and the unrelated distractors. Thus, the fixations were rather evenly distributed in the Difficult trials which suggests that participants systematically explored the entire set of stimuli before coming up with a solution. In Easy problems, the pattern was less even. A was significantly lower than all the others except UnDis and only marginally significantly from B, whereas C and Target, were significantly higher than others and did not differ one from the other. The comparison between Easy and Difficult trials revealed more A fixations in the Difficult trials.

In *Slice 3*, in both Easy and Difficult problems, not surprisingly, the proportion of looking times was higher for T than any other stimuli. In Difficult problems, the UnDis were significantly less looked at than B and C. The comparison between Difficult and Easy trials revealed lower proportions of gazes at T in Difficult trials than in Easy trials, and more C in Difficult than in Easy trials. This makes sense: in Easy trials, participants do not need to check the other options and look confidently at the solution whereas in Difficult trials, checking both T and C is important to be sure that one has the correct solution.

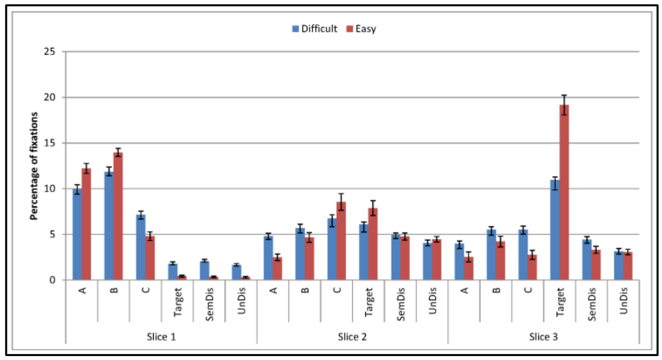

Figure 2: Mean percentage of fixation of each Type of Stimulus in first middle and last slice in Easy and Difficult trials (error bars represent SEM).

Transitions We also analyzed the transitions (saccades) between stimuli. Transitions tell us which stimuli are compared at a given moment of time. We focused on a subset of 8 transitions which have meaning (see Thibaut et al. 2011; Thibaut & French, submitted). The subset was composed of AB, CT(arget), AC, BT, BC, and also CSemDis, CUnDis, and TSemDis. The first four transitions are crucial to determining whether participants follow projection-first, constructive strategies (AB then CTarget), or alignment-first strategies (AC and BT) or a combination of both, depending on the moment of the trial. The last three transitions refer to comparisons between C and the solution set and between the two items which are semantically related to C (See Thibaut et al. 2011; Thibaut & French, submitted, for discussion of these transitions). We ran a three-way repeated-measure ANOVA with Transitions (AB, CT, AC, BT, BC, CSemDis, CUnDis, TSemDis), Slice (first, middle, last), and Condition (Easy, Difficult) as within-subject factors. The most important result was the significant interaction between these three factors, Type of Transition, Condition and Slice, $F(14,266)=13.13$; $p<.0001$; $\eta^2_p=.409$ (see Figure 3)

A posteriori comparisons (Tukey HSD) revealed that, in the *first slice*, there were higher rates of AB and BC transitions than all the other transition types, and of AB than BC transitions for both Easy and Difficult problems. The only significant difference between Easy and Difficult trials was that there were higher rates of AB transitions in the Easy problems. In the *second slice*, in the Difficult trials, there were significantly higher rates of AB transitions than other transitions types, of BC than AC, BT and CUnDis. In the Easy trials, there were higher rates of AB than CT, AC, BT and TSemDis transitions, of BC than all the other types and of CSemDis than CT, AC, BT, and TSemDis, and of CUnDis than AC and BT. The comparison between Difficult and Easy problems revealed a significantly higher percentage of AB transitions in Difficult problems and significantly higher percentages of BC and CSemDis transitions in the Easy problems.

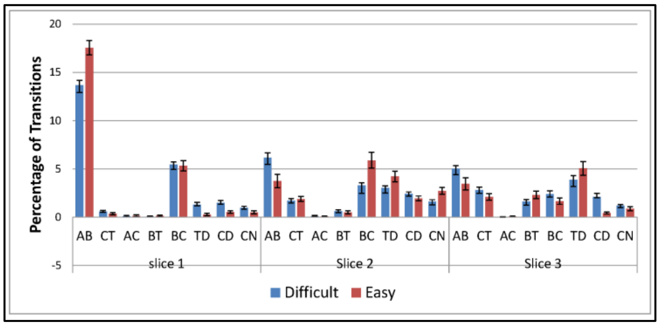

Figure 3: Mean percentage of each type of saccade in each slice in Easy and Difficult trials (error bars represent SEM).

In the *third slice*, in Difficult trials, there were higher rates of AB than all the other types except TSemDis, of TSemDis than AC, BT, CSemDis and CUnDis, of BC than AC and of CSemDis than AC. In Easy trials, there were higher percentages of TSemDis than any other types, of AB than AC, BC, CSemDis and CUnDis, and lower rates of AC than CT, BC and BT. Comparing Difficult and Easy trials revealed significantly higher rates of AB and CSemDis transitions in the Difficult trials. Most likely participants tried to re-represent the relation between A and B after looking at the solution set because they did not find the solution at first glance.

To summarize, results showed that gazes at A and B and AB transitions dominated in both types of trials at the beginning of the trials. Progressively, participants studied the solution set together with C. There were higher percentages of AB transitions in the first slice of the Easy than in the Difficult trials. The reverse pattern was true in the second and third slices. This suggests that more comparisons and redescriptions were necessary in the Difficult case. Importantly there were virtually *no AC* transitions in the three slices. The same was true for BT transitions except in the third slices in which there were more of them than AC and CSemDis transitions.

Discussion

By comparison with previous eye tracking studies, our paper extends them using analogies involving words rather than images. Bethell-Fox et al. (1984) used analogies defined around perceptual dimensions, whereas both Gordon and Moser (2007) and Thibaut et al. (2011) used pictures of objects and scenes.

The first purpose was to assess whether and under which circumstances participants tended to use project-first or align-first strategies (see introduction). Data confirmed the studies described above showing that there were higher rates of AB and CT saccades in participants' patterns of visual search than of AC and BT saccades. This confirms that, overall, participants mostly infer the relation between the pictures in the A:B pair (AB saccades) and apply it to the C-solution set (CT saccades). Results showed that both Easy and Difficult problems did not elicit AC or BT comparisons, i.e. alignments. A priori, it could have been argued that Difficult trials would require more alignments than Easy problems (Markman & Gentner, 1993). As will be seen in the next paragraph, Difficult and Easy trials differed in other ways.

The second purpose was to assess the impact of trial difficulty on the time course of the search for a solution. Our hypothesis was that adults would attend more to distractors, in Difficult trials, because the relation between A and B would not give an immediate obvious solution. This would lead participants to check the other part of the problem in order to find possible relations that would be applied to the AB pair. Hence, participants might have to re-represent the source domain more often later in the trial in Difficult than in Easy trials. Overall this hypothesis was confirmed by the data. In Difficult trials, in the *first slice*, participants evaluate a large set of possible solutions and are less focused on the source pair. Their orientation toward the solution space during the first slice is confirmed by their higher rate of fixation on T, SemDis, and UnDis, by comparison with Easy trials. In the *second slice*, participants made more AB saccades, which suggests that they made more returns to the source domain than in the Easy trials (see Bethell-Fox et al., 1984 for similar results). Also, they spent more or less the same time on all the stimuli for Difficult trials which was not the case in Easy trials in which there were more positive or negative peaks. This even distribution is the indication that the solution was not obvious. Maybe participants were trying various hypotheses or had no real hypothesis, or tried to re-represent the relation between A and B after the test of their first hypothesis at the light of what was found in the solution set. However, in Bethell-Fox et al. terms (1984), this is consistent with the idea that at this stage no response had been eliminated, even the non semantically related distractors (UnDis). This was confirmed in the *third slice*. Interestingly, the lower proportion of T fixations and the higher proportion of fixations at C in Difficult trials make sense since checking both T and C is important to be sure that T is the correct solution, which is not the case in Easy trials.

Third, we wanted to study the role of Distractors in both conditions. Rattermann and Gentner (1998) proposed that object matches are processed before relational matches, even in the adult case. Gordon and Moser (2007) found no evidence of this object matches primacy in their eye tracking data. They showed that relational matches appeared before object matches. Our data provide no conclusive evidence in one direction or the other. Looking times and transitions involving the Target and the SemDis were equivalent in the first slice. Participants looked at both possibilities in the beginning of the trial, particularly in the Difficult condition.

A fourth prediction was that participants might have to re-represent the A:B pair after seeing the solution set in Difficult trials more than in the Easy trials. This is compatible with the larger fixation percentages on A and B, and the larger rate of AB saccades in Difficult trials than in Easy trials at the end of the trials. This is also consistent with the idea that participants were still trying to test interpretations of the A:B pair at the end of the trial. To what extent this is a true re-representation is an open question. It might also be, at the end of the continuum that participants came back to A:B to check whether the interpretation they chose before was correct.

In conclusion, the trials difficulty influenced performance and the time course of the trial, even though the easy and the difficult shared the same global shape. More generally, the time course of our verbal analogies was similar to previous results. Difficult trials generated more explorations of the distractors and of the A:B pair.

Acknowledgements

This research has been supported by a Fondation Fyssen grant awarded to the first author, a French ANR Grant 10-BLAN-1908-01, ANAFONEX to the third author, a joint ANR-ESRC grant 10-056 GETPIMA to the second author, and a grant from the Conseil Regional de Bourgogne to the first and the third authors.

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