In the Eyes of the Beholder: What Eye-Tracking Reveals About Analogy-Making Strategies in Children and Adults

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Abstract

The present study uses eye-tracking technology to track differences in how children aged 5 and 8, and adults explore the space of possible answers to a semantic analogy problem. The main results were that adults looked more to A and B than to C and Target and that they start with A and B before looking at C and D. For children, the pattern was very different. They spent significantly more time than adults on C and the Target item (or distractors) and less on A and B. In addition, children start with an evenly distributed exploration of the stimuli before progressively converging on the C-Target relation.

Keywords: Analogy-making, development, strategies, eye tracking executive functions.

Introduction

Extensive work suggests that analogy-making, in the sense of understanding and/or generating relations between objects or situations in the world, is a cognitive ability that develops only gradually (Gentner, 1988, Goswami, 1992).

There are two main explanations of the development of the ability to make analogies. First, analogy-making can be explained in terms of the gradual increase of children's structured knowledge of the world (Goswami & Brown, 1990; Vosniadou, 1995; see Thibaut, 1999, for a general overview of conceptual development). According to Goswami (1992, 2001), it is only the lack of conceptual knowledge in one of the domains involved in the analogy that prevents children from deriving the correct analogies. This view attaches little or no particular importance to processing constraints. An alternative explanation, however, is based on the development of children's executive functions, and more particularly to their inhibition capacities and their cognitive flexibility. This explanation provides an explanation of observed analogy-making behavior for problems in which salient associations come immediately to mind, but are, in fact, irrelevant to the current analogy problem or when salient distractors are present in the solution set (Richland, Morrison, and Holyoak, 2006; Thibaut, French, & Vezneva, 2010a and b).

In order to test the role of executive functions in analogy-making in children, Richland, Morrison, & Holyoak (2006) used scene analogy problems consisting of pairs of scenes illustrating relations between objects. When there were distractors perceptually similar to the focal item in the base scene, children made more errors than when the distractors were perceptually dissimilar from the focal item. Thibaut, French, Vezneva (2010a) used geometrical shapes. In an A:B::C:D paradigm, children were influenced by the type and number of perceptual distractors. Thibaut, French, and Vezneva (2010b) studied the role of the semantic association strength between items making up the A-B and C-D pairs with 4- and 5-year-old children. They hypothesized that younger children, having more limited cognitive resources, would have more difficulty solving problems in which the A-B items and the C-Target pairs were weakly associated. In a classic A:B::C: ? paradigm with four possible responses, they compared weak and strong analogies (i.e., analogies in which the items of the A-B and C-D pairs were weakly, or strongly, associated) and manipulated the number of semantic distractors (1 or 3). Their results revealed a difference between weak and strong analogies, especially when the number of distractor items was high (i.e., three). This is compatible with the idea that a greater number of related distractors would be harder to inhibit (and thus, ignore) than a single semantic distractor. Interestingly, strong analogies were largely unaffected by the number of distractors, most likely because the relations between A- B and C-D item pairs were sufficiently strong that they were not interfered with by the semantic distractors. In contrast, when the problem involved weakly associated items, mapping the A-B pair onto the C-D pair requires more than simply accessing the obvious semantic dimensions of the items.

For this reason, we consider analogy-making to be a search through a space of features and potential relations. The number of relations holding between any A-B pair is potentially large because, depending on the context, any number of different relations might be relevant (see Murphy and Medin, 1985; Chalmers, French & Hofstadter, 1992; Hofstadter et al., 1995; French, 1995; Mitchell, 1993; Thibaut, 1991; 1997). As mentioned above, the structure of the search space and the presence or absence of competing non-analogical solutions have an effect on the search, especially for young children, who have greater difficulty handling the cognitive load associated with a more elaborate search of the space of possible solutions.

Goals of the present paper

The purpose of the present contribution is to study the development of analogy making with a combined set of measures – namely, the percentage of correct answers, the locus of the errors, and eye tracking measures – in a task in which we manipulate the number of distractors and the semantic strength in the A-B pairs and the C-D pairs (see Thibaut et al. 2010b). By means of an eye-tracker, we were able to record exactly where participants looked in their quest for a solution, which allowed us to develop a better idea of how a solution to a particular problem arose.

These measures of performance and eye-gaze position are well suited to the study of cognitive control, in general, and to the integration of the various sources of information that are available during the task. Richland et al. (2006) and Thibaut et al. (2008 or 2010b) used a “percentage correct” measure to assess performance. They were not able to directly address the question of *how* the search of solution-space actually took place, that is its temporal and dynamic dimensions. In Experiment 2 in Thibaut et al. (2010a), the authors were able to make some progress on this front by recording RTs, as well as percentage-correct responses. However, eye-tracking was the tool needed to study these search strategies correctly.

Most models of analogy making for problems of the A:B::C:? type assume there is a mapping process between items. It is often thought that they first have to find the relation between A-B and then they search for a solution, D, such that when this relation is applied to C, it produces D. This is also described as mapping the A term onto the C term and the B term onto a D term (see French, 2002; Gentner & Forbus, 2010, for reviews).

It is clear that the knowledge approach (Goswami, 2001) does not make explicit predictions regarding the processes that are involved. Even the executive function approach falls short of a good description of the temporal dynamics of how an analogy is found, particularly the temporal dynamics leading to a solution.

The temporal dynamics of children’s and adults’ explorations of solution-space during analogy-making currently remain, to a large extent, unexplored. How the mapping process is organized, how children explore the set of stimuli that compose the task (i.e., the base, the target and the other items composing the proposed solution set) to come up with a solution, etc. are largely unknown. In an eye-tracking study of analogy-making using scenes from Richland et al. (2006), Gordon & Moser (2007) found that adults initially focused on the actor-patient first in the source image (analogous to our A and B items) and then looked for the solution in the target image (analogous to our C and D terms).

However, to the best of our knowledge, eye tracking has not been used developmental studies of analogy making. How long do participants study each type of stimulus (Base, target, distractors)? Do children and adults have the same looking profiles? Crucially, how much time is spent on each stimulus with respect to the time course of a trial? For example, do children first spend their time looking at A-B before they analyze C and the potential solutions? As mentioned above, it is often claimed that structure mapping starts with the determination of the relation holding between A and B which is later applied to C and D. For example, for Leech, Mareschal & Cooper (2008), solving an A:B :: C: ? analogy involves first extracting an a priori relation, *R*, between A and B and then applying this relation to find a D that goes with C. This so-called “relational priming” view depends on the existence of context-independent features and relations.

Eye-gaze transitions between stimuli (e.g., gaze focus on item A followed by a gaze focus on item C) provide crucial information regarding the organization, if any, of the search. We recorded the eye movements of children aged 5 and 8 and adults who were asked to solve semantic analogies containing none or 1 semantically related distractor. The idea behind the 0 distractor case was to study the organization of the search when the solution becomes more obvious. Analogies were constructed around weakly or strongly semantically associated pairs. For example, *man-plate* is a weakly associated pair (people eat from plates) or *bird-nest*, a much stronger, immediately accessible association.

Experiment

Participants

Seventy-one participants took part in this experiment: 26 5-year-old children (M = 5;7 months), 25 8-year-old children (M = 8;8), and 20 adult university students (M = 21;7). Informed consent was obtained from parents for the children.

Materials

The experiment consisted of 14 trials, divided into 2 practice trials and 12 experimental trials. A 2x2 design was used with Association strength (Weak or Strong) x Number of distractor (0 or 1).The design of each trial was of the A:B::C:? type. There were three trials per condition. Each trial consisted of 7 drawings: items A, B and C and the solution set that was composed of a row of 4 drawings that included the analogical match and three distractors. There was either 1 distractor that was semantically related to C and 2 unrelated distractors (1-Distractor condition) or 3 distractors that were semantically unrelated to C (0-Distractor condition). We systematically varied the positions of the solution and distractor items in the solution set (see Figure 1).

The strength of the semantic association between pairs of words and their corresponding picture was determined by university students. They were asked to rate to what extent each item of a pair made them think of the other. It was stressed that the task was to rate how strongly the two items were associated in their mind. The ratings were on a 1-to-7 scale. On the basis of these results, we were able to construct pairs of stimuli that were either strongly related or weakly related. In the strongly associated condition, the semantic association strengths for the strong pairs (A-B, C-D, C-semantic distractor) was significantly higher than the corresponding strengths for the pairs in the weak condition.

The experiment was run with E-prime® software. We used a Tobii T120 to record participants’ gazes.

Procedure

Two experimenters saw the children individually at their school in a quiet room or at the university for the adults. Participants were seated in front of the Tobii screen. For each participant, the experiment started with a calibration phase which followed the protocol specified for the apparatus.

Each trial began when the experimenter pressed the space-bar. The 7 stimuli for each trial were displayed simultaneously. The A:B pair and the C item were shown in an array with the first two items grouped together to the left of the screen. The C item was alone on the right of the screen and next to C there was a box with a question mark. The four solution items were displayed on a separate row, beneath the A B C ? row. Children were asked to point to the item in the lower row that best completed the series of items in the upper row (cf. Goswami & Brown, 1990). The first two trials were training trials and children received feedback: the experimenter explained in what terms the Target was the correct solution and incorporated the relation holding in the A-B pair in his/her demonstration. The reaction times were recorded by the experimenter who started timing at the beginning of each

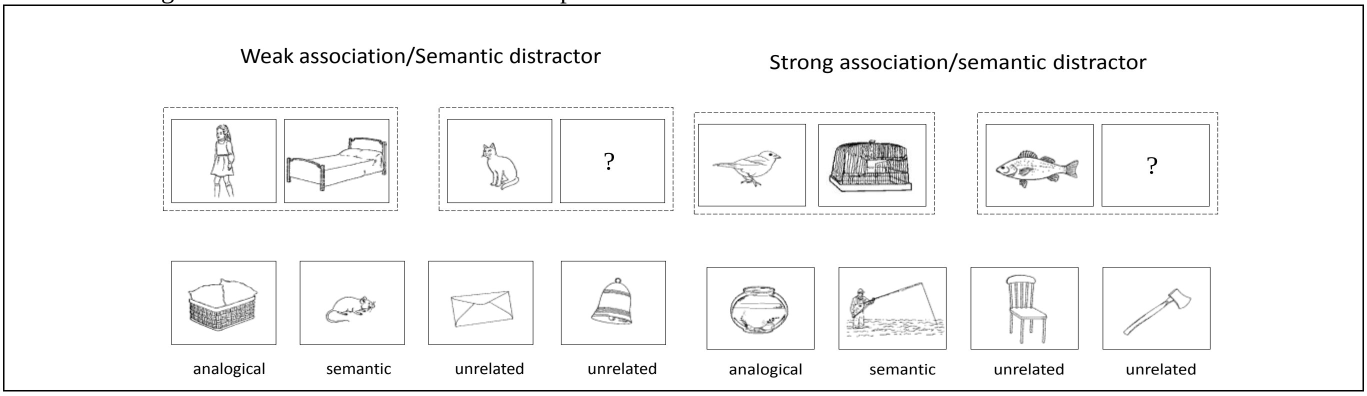

Figure 1: Example of strong and weak analogies with a semantically related distractor in the solution set. In the 0 distractor conditions, the semantically related distractor was replaced by an unrelated foil.

trial. Participants were instructed that they were to point to the stimulus on the screen corresponding to their choice “as soon as they had found the solution”. They were told that they were to point to only one stimulus per trial. The experimenter stopped timing the participant when he/she pointed to a solution.

Afterwards, children’s understanding of the semantic relation between A and B and between C and D was assessed. They were shown the A:B pairs and were asked *why* the two items of each pair went together. The same was true for the C-D pairs. This was done for the 12 trials of the experiment.

Results

We conducted several analyses: performance (number of correct responses), looking times for each of the 7 stimuli defining a trial, and the first-order transitions between the stimuli (i.e., the time spent between the stimuli A and B or between A and C).

Performance was measured as the percentage of valid relational matches. As in previous papers (see Thibaut et al., 2010b) we eliminated all trials in which either the children did not understand the semantic relation between the A and B items or between the C and D items. Indeed, we wanted to avoid cases in which failure would result from an absence of the relevant knowledge.

We ran a 3-way mixed ANOVA on the data with Age (5, 8, Adults) as a between factor and Association strength (strong vs. weak) and Distractor-type (0 or 1 semantic distractor) as within factors.

As expected there was a main effect of age, $F(2, 68) = 37.58$, $p < .0001$, $\eta^2 = .52$, a main effect of number of distractors, $F(1, 68) = 78.2$, $p < .0001$, $\eta^2 = .53$, a main effect of association strength, $F(1, 68) = 5.4$, $p < .05$, $\eta^2 = .07$, and an interaction between number of distractors and age, $F(2, 68) = 15.57$, $p < .001$, $\eta^2 = .31$. This interaction results from the virtually perfect performance for the 3 age groups in the 0-distractor condition compared to the much worse performance (< 60% correct) in the 1-distractor condition for 5- and 8-year-olds, whereas adults were 97% correct. These results confirm previous results obtained by Thibaut et al. (2010b) in which the presence of distractors decreased performance. They also confirm that analogies based on weaker associations between A and B and between C and D were more difficult than analogies based on strongly associated pairs.

In this experiment, we were primarily interested in the distribution of looking times on the 7 stimuli composing the task. First, the analyses that will be presented were done only on “correct” trials (i.e., in which the correct answer was given). Indeed, it is difficult to figure out what happens in “error” trials: children might have failed because they answered randomly, or ignored some of items shown or whatever. In order to perform this analysis, we first defined a criterion to include data in the analysis. Indeed, there were a number of cases in which participants looked away from the screen during a trial or in which participants, especially 5-year-olds, were correctly looking at the screen but their gazes were not recorded for various reasons (reflections on glasses, body movements, suboptimal orientation of the Tobii screen). These difficulties are well known with this technique (Duchowski, 2007). We discarded a trial from the data set when more than 20% of looking times were missing for this trial. With these criteria (correct trials and trials with more 80% or more of looking times), we kept 8 five-year-olds, 15 eight-year-olds, and 19 adults. We lost many young participants because they made more errors and had more “20%-or-more” trials resulting in more empty conditions.

We ran a 4-way mixed ANOVA on the resulting data with Age (5, 8, adults) as a between factor and Association Strength (weak, strong), Number of Distractors (0, 1), and Items (A, B, C, Target, Distractor – semantically related in the 1-distractor condition, absent in the 0-distractor condition) as within factors. Of central importance are the interactions between Age and the other factors.

There was a main effect of Association strength, $F(2, 39)=11.15$, $p<.005$, $\eta^2 = .22$, with longer looks in the weak condition than in the strong condition (M = 0.98s and .81s, respectively). This is compatible with our hypothesis that in the weak case, the search is more open. There was a main effect of Age, F(2, 39)=84.66, p<.0001, η^2 = .81, of Items, F(6, 234)=136, p<.00001, η^2 = .78, an interaction between Items and Age, an interaction between Association strength and Items. Both were subsumed by a triple interaction between Association strength, Age and Items, F(12, 234)= 2.38, p<.01, η^2 = .11 (see Figure 2). There was also an interaction between association strength and distractors and a triple interaction between Association strength, number of distractors and Age, F(2, 39)=4.21, p< .05, η^2 = .17. We will concentrate on the triple interaction between Association strength, Items and Age. Figure 2 shows that 5- and 8-year-olds spent much more time on C and D than on A and B which is not the case for the adults. This important result suggests a major difference between children and adults while exploring the stimuli. As Figure 2 shows this does not mean that younger children spend less time on the A-B pair than adults but, rather, that they tend to spend relatively more time on C and D than on A and B, whereas the adults tend the distribute their looking times more evenly on these two pairs. This is consistent with the idea that they first try to find the stimulus that goes with C and might be less concerned with information regarding A and B. Note that the difference between children and adults was not due to the fact that adults did spend less time, overall, exploring the stimuli. As mentioned above, there was no difference between children and adults for A and B. Note also that the 0-1 distractor conditions are fused in this interaction, thus the value that is reported for D is a mean from 0 and 1 distractor trials.

Figure 2 also reveals that adults spend less time on the unrelated distractors than younger children in the case of weakly associated analogies. This is consistent with our hypothesis that in this case, the search space is broader and that children are required to explore it more thoroughly to find a solution and take more time to reject these solutions than adults who, very quickly disregard the unrelated distractors.

We performed the same analysis as above, but divided each trial into 3 time slices. The main purpose was to

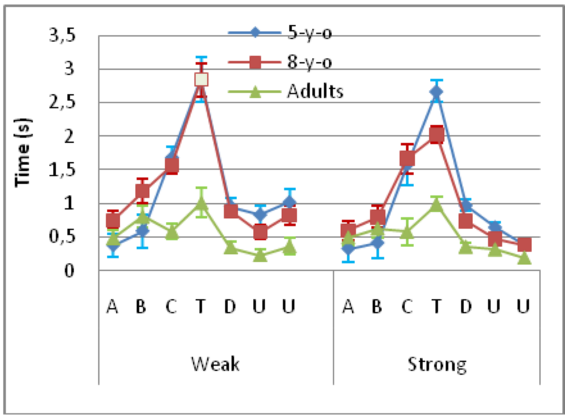

Figure 2: Interaction between Age, Items and Association strength. T, D and U stands for Target, Distractor and Unrelated respectively.

compare the age groups in terms of their allocation of search time on each type of stimulus as a function of the time slice. In this particular analysis, we discarded the 5-year-olds. Because of the missing data (due to the fact that we concentrated on correct trials, less frequent in this group, and because; also each empty cell, more frequent for younger children, meant that the corresponding participant was lost in the analysis), only 5 children remained in the data set. However, overall their data profile was very similar to that of the 8-year-olds. In order to simplify the design, we also removed the unrelated stimuli from the analysis and the no distractor condition. The latter was done in order to concentrate on the conflict between the Target solution and the semantically related distractor. (The interested reader should contact the first author to receive the complete analysis). We ran a 4-way mixed ANOVA on the resulting data with Age (8, adults) as a between factor and association strength (weak, strong), items (A, B, C, Target, Distractor) and Slice (1st, 2nd, 3rd) as within factors. We were mainly interested seeing if there was an interaction involving Age and Slice. There was a main effect of Age, Slice, Items, five double interactions (Slice x Age, Items x Age, Slice x Association strength, Slice x Items, Association strength x Items). We will not describe them here for the sake of brevity.

The main result was an Age x Slice x Items triple interaction, F(8,176)=4.77, p < 0.001, η^2 = .18. Figure 3 clearly shows one major difference between the two age groups. Adults spend the majority of their time exploring the A-B stimuli, then the time they devote to these two stimuli decreased in favor of C and the Target in slices 2 and 3. By contrast, 8-year-olds distribute their looking-time across the 5 items relatively evenly in the first slice, and then they progressively converge on C and D, whereas B and the distractor receive less of their attention. Adults, by contrast, show two distinct peaks of attention, the first one on A and B, and the second one on C and D.

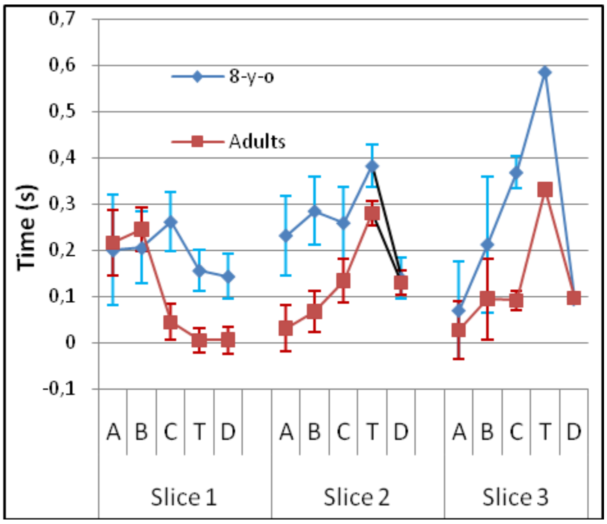

Figure 3: Age x Items x Slice interaction. Items A, B, C and T (Target) and D (Distractor).

Finally, we analyzed the first-order transitions between items. For example the AB transition is the time spent looking from A to B or the reverse. Note first that the entire set of possibilities is a 7 x 7 matrix, that is 49 possibilities for each of the 4 conditions included in our design (e.g., weak-no distractor condition, weak-1-distractor condition). Most of these transitions occur very rarely, if at all (e.g. a transition between A and an unrelated distractor). Overall, the transition times were much shorter than the looking times to the stimuli themselves. In fact transitions correspond to saccades between stimuli. Thus, more saccades means longer looking times devoted to transitions. We decomposed the problem into 2 separate analyses. In the first one, we evaluated the number of AB, BC, CT transitions (T is the Target item) as a function of Age, number of distractors, and association strength. We ignored the AC and BT transitions which rarely appeared in the data. The second analysis was performed on transitions between stimuli in the data set. We will not present these data. We ran a 4-way mixed ANOVA on the data with Age (5, 8, adults) as a between factor and Association strength (weak, strong), number of distractors (0, 1), and Transitions (AB, BC, CT) as within factors. Results revealed main effects of Age,

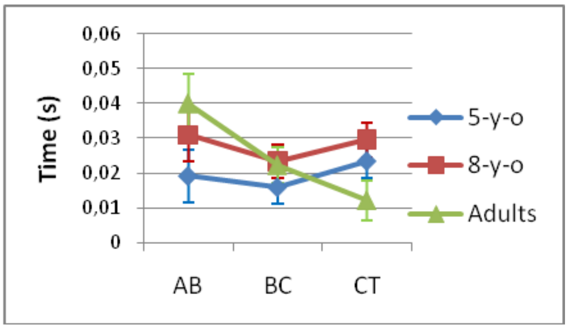

Figure 4: Age x Transition interaction. The analysis was restricted to the AB, BC and CT transitions (T = Target).

$F(2, 68) = 3.4$, $p < 0.05$, $\eta^2 = .1$, Transitions, $F(2, 136) = 14.9$, $p < .0001$, $\eta^2 = .18$, a significant Age x Transitions interaction, $F(4, 136) = 12.7$, $p < .0001$, $\eta^2 = .27$, and a significant Association strength x Transition interaction, $F(2, 136) = 7.1$, $p < .005$, $\eta^2 = .09$. The Age x Transition interaction shows that adults spent more time going from A to B than going from C to the Target (Figure 4). By contrast, children distribute the transitions more evenly. Interestingly, the AB transition gets more attention as age increases and the CT transitions less. Again, this is compatible with the idea that adults first analyze the A-B pair and once they have found the semantic relation holding between them, they apply it very quickly to C and T (target).

General discussion

The present experiment was the first attempt that we are aware of to characterize the development of analogy making with eye tracking measures. (Gordon & Moser, 2007, involved only adult participants.) We were able to follow the unfolding of the search from the presentation of the analogy problem to the decision itself. Our results suggest that adults initially pay attention to the A-B pair at the expense of the other items and, only later, do they converge on the C-D pair. This transition is clear cut. By contrast, children first allocate their attention evenly across the various items and converge progressively on C and the solution.

To recapitulate, performance measures in this experiment confirm Thibaut et al. (2010b) which showed that the presence of distractors decreased performance and that “strong” analogies were easier to solve than “weak” analogies. This result is not predicted by Goswami and Brown’s (1990) purely knowledge-based account of analogy-making. The strength of an association should not matter, only the knowledge of it.

The eye-tracking results showed that adults did not spend the same proportion of time on the different types of stimuli as children did. In fact, adults spend much less time on C and the Target item than children, which is consistent with the idea that they first analyze the A-B pair and generalize quickly on the basis of this analysis (see Thibaut et al., 2010a for a similar proposal). It is important to note that adults spend less time on the unrelated distractors than 5-year-olds in the weak analogy case (see Figure 2). This is compatible with our idea that weak analogies define a broader space in which solutions do not come to mind immediately. Consequently, younger children must explore this space more completely in order to find the solution (note that this condition is more difficult for them than the strong case). By contrast, adults do not need this exploration time to discard the unrelated distractor items.

This was confirmed by our analysis of the time slices (see Figure 3). At the beginning of a trial, children distributed their time evenly across the five types of items (A, B, C, T (target), semantic Distractor) and converge progressively on the CT pair (slice 3). Slice 2, compared to Slice 1, showed a more uneven profile for the 8-year-olds compared to the Adults. Slice 3 shows convergence on C and Target and less attention paid to A and to the Distractor. The allocation of time in Slice 2 and 3 is not the same since only Slice 3 displayed the peak on C and the Target. For adults, however, the pattern of exploration is markedly different from that of children. There is a sharp contrast between the large amount of time allocated to A and B compared to the time allocated to C, Target and distractor in slice 1. Adults then converge sooner on C and the Target (slice 2) than children. This is consistent with the idea that adults first try to interpret the relation between A and B and map it later on C and Target. Children, by contrast, explore the space more evenly, and converge progressively on the C-Target pair. With children, we did not find any evidence of the same clear cut “first A-B then C-Target” pattern that we found in adults.

In addition, the analysis using transitions showed an analogous pattern. Children allocated the same amount of time to the 3 types of transition whereas adults had more AB transitions than CT transitions. Again the latter result is consistent with the idea that adults first try to interpret A-B, and do not need many transitions to find the Target that has the equivalent relation with C. This was not the case for children (Figure 4).

This pattern of results, we believe, is compatible with the executive function account. The task that we used here is a classical paradigm in the study of analogy which focuses on C and the target but requires the integration of A and B in the search process. This is perfectly done by adults who seem to organize their search around the relation between A and B. By contrast, children seem to organize their search around C and D (the central point in this task) and pay less attention to A-B. Particularly, at the beginning, they are unable to focus on particular stimuli and distribute their attention evenly across stimuli. In other words, they are less able to inhibit their attention to particular stimuli. At the end of their exploration, they still pay more attention to C and the distractor than adults who focus on the target.

How does this relate with models of analogy making? Leech et al. (2008) recently proposed a “relational priming” model in which analogy making in children is explained in terms of a priming of the C-Target relation by the AB relation. Interestingly, this model has been devised to account for A:B::C:? data. While, at least for strong analogies, the model might be applied to the adult case, in the sense that they first analyze A and B and apply the relation to C and Target (although we cannot confirm that it is a priming phenomenon), we found no evidence of such a “first find AB relation, then apply it to C” pattern in children. By contrast, they pay more attention to C and D at the beginning of the analogy making process. We believe that the executive function view provides a better framework to account for the data. Children pay more attention to distractors or unrelated stimuli than adults.

In conclusion, we have presented work that compare children’s and adults search profiles in with different types of analogy problems and found major differences between adults and children. In the future, it will be interesting to reconstruct more precisely the trajectories of the different groups and to compare the patterns obtained for correct and wrong answers.

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