Journal of Experimental Child Psychology 106 (2010) 1–19

Contents lists available at ScienceDirect

Journal of Experimental Child Psychology

journal homepage: www.elsevier.com/locate/jecp

The development of analogy making in children: Cognitive load and executive functions

Jean-Pierre Thibaut *, Robert French, Milena Vezneva

Department of Psychology, University of Burgundy, 21065 Dijon Cedex, France

ARTICLE INFO

Article history:
Received 23 June 2009
Revised 1 January 2010
Available online 12 February 2010

Keywords:
Analogy
Executive function
Development
Proportional analogy
Perceptual–relational competition
Inhibition
Generalization
Cognitive load

ABSTRACT

The aim of the current study was to investigate the performance of 6-, 8-, and 14-year-olds on an analogy-making task involving analogies in which there are competing perceptual and relational matches. We hypothesized that the selection of the common relational structure requires the inhibition of other salient features, in particular, perceptual matches. Using an A:B::C:D paradigm, we showed that children's performance in analogy-making tasks depends crucially on the nature of the distractors. Children chose more perceptual distractors having a common feature with C compared with A or B (Experiment 1). In addition, they were also influenced by unstructured random textures. When measuring reaction times instead of accurate responses, only the 8-year-olds' reaction times were significantly influenced by perceptual distractors. The 6-year-olds seemed to select the first match they noticed, and the 14-year-olds were not influenced (or much less influenced) by featural distractors. These results are compatible with an analogy-making account based on varying limitations in executive functioning at different ages.

Introduction

Analogy making is, without question, one of the most singularly important ways in which children gradually make sense of their world. Certain authors (cf. Hofstadter, 2001) have gone so far as to claim that it is *the* most important cognitive mechanism underlying not only development but all of cognition. We investigated the development in children of the mechanisms underlying analogy-making

* Corresponding author.
E-mail address: jean-pierre.thibaut@u-bourgogne.fr (J.-P. Thibaut).

0022-0965/$ - see front matter
doi:10.1016/j.jecp.2010.01.001

abilities. Various tasks have been used to study whether and under which conditions children grasp the relations between various situations. These include the Duncker's problem (Duncker, 1945), the Genie task (Holyoak, Junn, & Billman, 1984), and the classical A:B::C:D task used in the current study.

In the developmental literature, there have been many attempts to study which factors can explain children's difficulties in solving analogies. One important view is that children fail to solve analogies because they lack the necessary knowledge to understand the relations involved in the analogies. A second view explains young children's failures by their less developed executive functions. Our experiments were designed in the latter context of the development of the so-called executive functions. We manipulated the nature and number of perceptual distractors in an A:B::C:D paradigm. A number of authors who have studied the developmental mechanisms of analogy making have also suggested that a gradual progressive improvement of various processing capacities—in particular, an increased ability to cope with cognitive load—is responsible for improved analogy-making skills with age (e.g., Halford, 1993; Richland, Morrison, & Holyoak, 2006).

Even though the construct of executive functions might not admit of rigorous definition—something that is, moreover, beyond the scope of this article—there is nearly unanimous agreement that executive functions refer to processes involved in the control of action and thought, either as a set of components, such as planning, decision making, judgment, and self-perception (Tranel, Anderson, & Benton, 1994; see also Zelazo, Carter, Reznick, & Frye, 1997), or as a single dimension of executive control, such as inhibitory control (e.g., Carlson, Moses, & Hix, 1998).

Executive functions have been invoked to explain the development of analogy making, a multifaceted ability. Crucially, analogy making involves selecting the information that is relevant to the analogy and rejecting the information that is not. For example, if A and B are a *bird* and a *nest*, respectively, and C is a *dog,* then D should be a *doghouse.* Distractors (e.g., bones, a cat), even though they are highly thematically or taxonomically related to C (the dog), must be actively rejected as solutions to the analogy. Halford, Wilson, and Phillips (1998) argued that one fundamental constraint acting on cognitive development is the maximum relational complexity, defined as "the number of related dimensions or sources of variations" (p. 803) that can be processed in parallel in working memory. This number increases with age. However, this linear trend has been contested (e.g., Goswami, 1998; Rattermann & Gentner, 1998). In Halford and colleagues' view, maturational changes in processing capacity represent the major impetus of development.

Similarly, Richland and colleagues (2006) stressed the importance in children's analogy making of specific abilities tied to executive functions, in particular, their ability to integrate multiple relations and to "inhibit tendencies to respond on the basis of competing superficial similarities" (p. 253).

The executive function view of the development of analogies contrasts with other views of children's capacities in analogy making. Certain authors have emphasized the role of domain knowledge, suggesting that increasing knowledge about relations in one conceptual domain will increase analogy making in the target domain (see Goswami & Brown, 1990; Vosniadou, 1995). According to Goswami (1992), analogical reasoning is already available during infancy (see Chen, Sanchez, & Campbell, 1997). According to this account, it is only the lack of knowledge in the conceptual domains involved that prevents children from deriving the correct analogies.

Gentner (1988), Gentner and Rattermann (1991), and Rattermann and Gentner (1998) suggested that a so-called "relational shift" occurs in many domains during development even though this shift does not occur at the same time for all domains. It is defined as a shift from early attention to featural similarities to later attention to common relational structures. After the shift, children will primarily succeed in analogical reasoning tasks because they are able to reason on the basis of relational features. Even though the distinction between attributes and relations is far from clear and, at the very least, is highly context dependent (Chalmers, French, & Hofstadter, 1992; French, 1995; Mitchell & Hofstadter, 1990), we concur that, in general, attribute matching seems to precede relation mapping in children, with the preference for the latter occurring earlier or later depending on children's familiarity with the domains involved (Gentner, 1988; Goswami & Brown, 1990; Rattermann & Gentner, 1998). However, as mentioned by Richland and colleagues (2006), there is no specification of the cognitive mechanisms that are involved in the relational shift.

According to a view dating back to the 1960s (e.g., Evans, 1968) that has recently been revived and given connectionist clothing by Leech, Mareschal, and 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 C. This view that depends on the existence of context-independent relations has been criticized by various authors (French, 1995; French, 2008; Hofstadter & Fluid Analogies Research Group, 1995; Mitchell, 1993; Thibaut & Schyns, 1995) who insist on the crucial role played by C in choosing the appropriate relation between A and B. Crucially for the studies in the current article, if the relation *R* were context independent, this would imply that once *R* was determined, its application to C should remain unaffected by the presence of distractors or potentially conflicting responses.

Analogy making and the development of executive functions

As mentioned earlier, Richland and colleagues (2006) hypothesized that limitations on the cognitive resources involved in processing would increase the difficulty of making analogies involving conflicts between perceptual matches (also called featural or attributional matches) and relational matches. Richland and colleagues used scene analogy problems consisting of pairs of scenes illustrating relations among objects and manipulated featural distractors by varying the identity of one of the objects in the second scene. So, for example, if the base scene had a running cat as its focal item, in the target scene the researchers included an object that was either perceptually similar to the focal item (e.g., a sitting cat) or dissimilar (e.g., a sandbox). Their results showed that the target scene with distractors that were perceptually similar to the focal item in the base scene elicited more errors than when the distractors in the target scene were perceptually very different from it. In addition, they showed that two-relation problems were more difficult that single-relation problems.

In our experiments in analogical reasoning, we varied the type and salience of competing relations, attributes, and nonrelevant distractors. We believe, like Richland and colleagues (2006), that the ability to perceive and map structures within and across domains depends on a *competition* between relations and attributes of the objects involved. The outcome of this competition depends on the degree of salience of the competing relations and attributes. In addition, it could be that, in certain cases, there might be no real competition between relations and attributes, as when younger children look for a certain type of match (e.g., a perceptual match) at the expense of the others. They might select the first stimulus that provides a match—*any* match—with one of the terms of the analogy (A, B, or C) and look no further. By contrast, older children might consider *only* relational solutions and neglect perceptual ones. In between, there might be real conflicting situations in which children first consider various possibilities, including perceptual and relational matches, before they decide. We consider these different possibilities, looking at patterns of errors and, in Experiment 2, comparing patterns of reaction times (RTs).

Overview of the current study

This study consists of two experiments, both of which use an A:B::C:?(D) paradigm in which children needed to find the D solution among several possibilities. We focused on the key notion of the competition (or interaction) between the perceptual attributes of the stimuli being processed and the relations between them. We attempted, insofar as possible, to remove semantics (i.e., world knowledge) from our experiments, relying exclusively on abstract shapes, colors, and (in Experiment 2) textures. We also wanted to provide a better control than in Richland and colleagues' (2006) study on the distinction between relational matches and perceptual matches. Finally, we modified cognitive load by varying the number of perceptual matches and the amount of perceptually distracting "texture" added to the test stimuli. We considered a number of different measures of performance—percentage correct, patterns of errors, and RTs.

Experiment 1 was a variation of a preliminary experiment (Thibaut, French, & Vezneva, 2008) based on the executive function framework in which we manipulated the number of perceptual distractors (zero, one, or three) as well as their type. We assumed that a greater number of perceptual distractors would increase cognitive load. Results revealed a significant effect of age and number of perceptual distractors. These results are consistent with the executive function framework developed in the article. However, in Thibaut and colleagues' study, the relational matches were also perfect perceptual matches on one dimension. For example, in the shape condition, if the base items were a pair of circles and the C item was a rectangle, the D solution was the identical rectangle. As a result, the analogical solution was both a relational solution (i.e., identity relation) *and* a perceptual solution (i.e., same rectangular shape) (see Fig. 1). To avoid the relational match also being a perceptual match, we made the relational match a perceptual transformation of the C term. For example, for a shape analogy, the D shape solution would have the same shape as the C shape but shrunk or elongated. For a color analogy, the color of the D item was darker than the color of the C item. Perceptual competitors were identical to the C item (or to the A or B item, depending on the condition) on one dimension value (see Fig. 2).

We wanted to study the distribution of errors on each of the three incorrect target choices. The analysis of the distribution of errors was designed to provide additional information regarding how the children produced their answers. Do their errors reflect the projection of the A or B term's features onto the possible responses, or do they rely primarily on the features of C for their answers? We compared two types of analogies: one based on color and the other based on the shape of the stimuli.

In Experiment 2, we manipulated what we called *perceptual noise.* Perceptual noise was implemented as an addition to the stimuli of random textures. This contrasted with a perceptual match that shared an obvious dimension value with the C term. We also introduced RT measurements to study the effect of different types of information on the time course of the analogy process.

In general, we expected that more perceptual competitors, as well as more noise, would increase the cognitive load associated with making the analogy, generating significantly more errors.

Experiment 1

In the classical A:B::C:? analogy-making paradigm, participants need to select a D term in such a way that the A:B and C:D pairs share a common salient relation. Bearing in mind the problem of establishing an a priori context-independent relationship between A and B, we designed A, B, and the "context term" (C) in such a way that there would be one best (and obvious) analogical solution. In the three conditions of the current experiment, we attempted to progressively increase the number of perceptual competitors (perceptual matches) among the distractors (i.e., the nonanalogical situations). We compared three groups of children: 6-, 8-, and 14-year-olds. We chose these three age groups because a preliminary experiment was composed of 4-, 6-, and 8-year-olds and we found that 4-year-olds could not understand the task. In Thibaut and colleagues (2008), we found clear differences between 6- and 8-year-olds. We included 14-year-olds because it is well known that significant changes in executive functioning occur around this age (e.g., Brocki & Bohlin, 2004).

This experiment had a $3 \times 3 \times 3$ design with age (6- vs. 8- vs. 14-year-olds) as a between-participants factor and with type of matching (identical shape vs. transformed shape vs. transformed color) and competition (no-competition vs. single-competition vs. three-competition conditions) as within-participants factors.

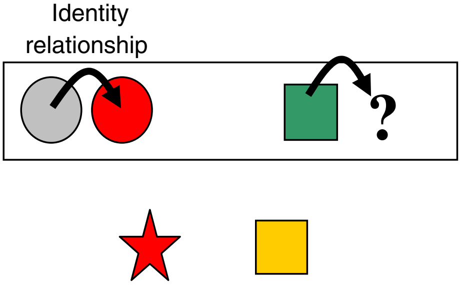

Fig. 1. The yellow square could have been picked not because of the identity relation between the two circles but rather because it shares a perceptual feature—namely, its square shape—with the green square. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

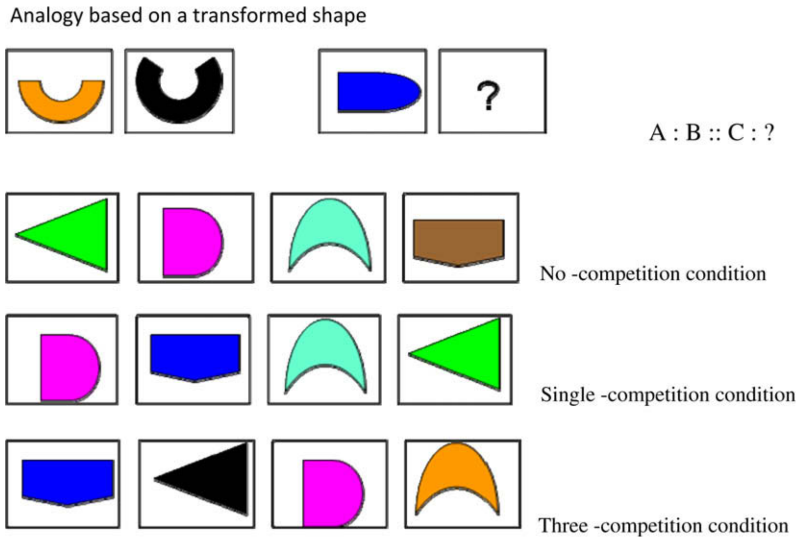

Fig. 2. Types of analogy used in Experiment 1. Here the shapes of B and D were extended upward compared with A and C, respectively.

Method

Participants

A total of 58 children participated in this experiment. There were 20 6-year-olds (14 boys and 6 girls, mean age = 78 months, range = 75–84), 20 8-year-olds (11 boys and 9 girls, mean age = 100 -months, range = 96–108), and 18 14-year-olds (10 boys and 8 girls, mean age = 174 months, range = 169–178). Participants were from middle-class families living in urban and suburban environments. They were tested in France (near Poitiers) and, for the 14-year-olds, in Bulgaria (Sofia). Milena Vezneva is a native Bulgarian who is also fluent in French. She translated the protocols into Bulgarian and ran the experiments in France and Bulgaria. A previous experiment (Thibaut et al., 2008) showed that there was no significant difference between French and Bulgarian participants for this kind of experiment. None of the children had ever repeated a year in school. We also included a control group composed of 10 adults to ensure that our analogies were not ambiguous. These participants from the University of Poitiers volunteered for this experiment.

Materials

Each trial had the A:B::C:? format. We called the first pair (A:B) the base pair and the second pair (C:?) the target pair. The two stimuli in the base pair were related by having, in the shape condition, the same shape or a similar but transformed shape or by having, in the color condition, a similar but transformed color. The third stimulus (C) needed to be matched with a fourth stimulus (D) such that the relation between C and D was the same as the relation between A and B (see Fig. 2). The D solution needed to be selected in a set of four stimuli. The experiment consisted of 18 experimental trials and 3 training trials. To obtain the 18 experimental trials, we crossed the three following factors: 3 types of matching (identical shape vs. transformed shape vs. transformed color) × 3 competition conditions (no-competition vs. single-competition vs. three-competition conditions) × 2 trials.

The three levels of the competition variable were as follows:

- the *no-competition* condition, in which there was only one relational item and three distractors that shared no obvious perceptual feature with the C term;

- the *single-competition* condition, in which there was one relational choice and three distractors, one of which was a perceptual match with the C term and the remaining two of which shared no obvious perceptual feature with the A, B, or C term; and
- the *three-competition* condition, in which there was one relational match and three distractors, each of which was a perceptual match, one with the A term, one with the B term, and one with the C term.

We compared shape and color analogies (referred to as the match condition). There were three types of analogies: two types of shape analogy and one type of color analogy. The first type of shape analogy was called the same shape condition. It replicated Thibaut and colleagues' (2008) shape condition, in which the relational choice was also a perceptual match in the sense that A and B had an identical shape and C and D also had an identical shape. In the second condition, the shape-transformed condition, A and B had the same shape except that B was a distorted version of A (e.g., if A was a rectangle, B was the same rectangle but shrunk or elongated) (see Fig. 2). The same was true for C and D; the shape of D was a distorted version (shrunk or elongated) of the shape of C. D was not identical to C on the analogical dimension, whereas the perceptual match on C was identical to C on another dimension. The third condition was the transformed color condition, in which the color of the D term was darker than the color of the C term (see Fig. 2). Shape and color analogies were mixed together as in Thibaut and colleagues' study because if all of the analogies had been of the same type (shape analogies or color analogies), once children had discovered in the easy (e.g., no-competition) trials that both A:B and C:D pairs consisted of identically shaped items (or, in the color condition, identically colored items), it would have been easy to apply this "rule" to all of the remaining trials.

For the 3 training trials, we constructed one "transformed color/no-competition" stimulus, one "same shape/three-competition" stimulus, and one "transformed shape/single-competition" stimulus.

Nine experimental lists were created. Any given shape (e.g., an arrow) or color could appear as either an A, B, C, or D item as well as an irrelevant stimulus across different lists to avoid any systematic pattern of choices that would be driven by children's preference for a given shape (or color) rather than by the constraints of the analogy task. In each list, the different types of trials were interleaved randomly. The 21 trials (3 training and 18 experimental) were put into a PowerPoint presentation (1 trial per slide). They were displayed on a 15-inch laptop screen. Each trial was composed of two rows of stimuli. The first row was composed of the A, B, and C items. The C term was alone on the right of the screen, and next to it was an empty square with a question mark. The second row, below the first one, was composed of four stimuli, one of which was the D solution. Each of the seven stimuli composing a trial was displayed in a 3.8-cm (height) by 4.4-cm (length) rectangular box (see Fig. 2).

A second list of stimuli was used in a control task for the two transformed conditions to assess children's understanding of the fact that A and the transformed B, as well as C and the transformed D, were similar shapes (or colors in the color analogies).[1] In the A:B case, the slide was composed of the A term and a question mark next to it. The four choices for the analogy task were shown to the children except that the actual solution (the D term) was replaced by the B term. In the C:D case, a slide was composed of the C term and a question mark together with the four solutions to the analogy task.

Procedure

At the start of the experiment, for the first training trials, children were told, "Let's play a game in which I'm going to show you colored shapes on this screen. You will have to look at these pictures. First, look at these three pictures [pointing to A, B, and C]. Now look here [pointing to the D slot with the question mark]. There is one picture missing. You have to search here [pointing to the second row of stimuli] for the one that would finish the row." In both the training and experimental trials, as in Goswami and Brown (1990), children received no feedback. However, throughout the experiment, children were asked to justify each answer immediately after having selected it.

[1] We did not check children's vision for colors. However, our posttest control revealed that all of the children correctly matched all of the transformed colors with the initial color.

After the experimental task was completed, a control task was run. The children saw the list of trials again (see ‘‘Materials” subsection above), one by one, and were told, ‘‘Choose the stimulus [among the four choices] that has more or less the same shape (or the same color) as this one [the C item].” This control task needed to take place after the experimental task; otherwise, children would have known that the D (i.e., transformed) item was the same as the C item. The rationale behind the transformed shape condition was that children needed to analyze the stimuli during the analogy task to find both the similarity between A and B and the similarity between C and D to be able to discover the analogy, something that was unnecessary in the same shape condition.

Results

The analysis was performed on the stimuli for which participants correctly associated the shape (or color) in A or C with the transformed shape (or color) in B and D in the control task described above. It was necessary to ensure that participants noticed that A and B, as well as C and D, had the same shape (or color). Children who were unable to notice that A and C are similar to B and D, respectively, would presumably also fail to discover the relations between A and B and between C and D that were explicitly built on these similarities. Keeping the corresponding trials in the data pool would have increased the noise of the data, including random correct answers, as well as errors due to a failure to notice a perceptual similarity rather than a failure to notice the relation based on these similarities. There was one error for the entire experiment that was made by an 8-year-old.

We did not include the adult control in the analysis because adults made no mistakes and, thus, there was no variance in the data set. Also, we ran this group to be sure that each analogy had only one unambiguous solution. We ran a three-way mixed analysis of variance (ANOVA) on the children's data, with age (6- vs. 8- vs. 14-year-olds) as a between-participants factor and with match dimension (identical shape vs. transformed shape vs. transformed color) and match condition (no-competition vs. single-competition vs. three-competition conditions) as within-participants factors. The dependent variable was the number of correct relational matches. The ANOVA revealed a significant main effect for each of the factors. There was a significant effect of age, $F(2, 55) = 19.79$, $p < .001$, $\eta^2 = .42$; the 14-year-olds ($M = 1.74$ of 2.00) had better performance than the 6-year-olds ($M = 1.28$), and the 8-year-olds ($M = 1.70$) were also significantly better than the 6-year-olds. There was a significant effect of the match dimension, $F(2, 110) = 22.18$, $p < .001$, $\eta^2 = .29$. A posteriori tests (Tukey's HSD, $p < .05$) revealed that the same shape condition ($M = 1.80$ of 2.00) did not differ significantly from the transformed shape condition ($M = 1.68$). These two conditions were significantly better than the transformed color condition ($M = 1.28$). There was a significant effect of the match condition, $F(2, 110) = 31.53$, $p < .001$, $\eta^2 = .36$. Post hoc analyses revealed that the no-competition condition ($M = 1.80$ of 2.00) differed significantly from the other two conditions, the three-competition ($M = 1.40$) and single-competition ($M = 1.55$) conditions, which did not differ significantly from each other.

There was a significant interaction between match condition and match dimension, $F(4, 220) = 6.82$, $p < .001$, $\eta^2 = .11$ (see Fig. 3). A Tukey's HSD ($p < .05$) in the shape condition revealed that there was a significant difference between the no-competition and three-competition conditions. In the transformed shape condition, there was a significant difference between the three-competition and no-competition conditions ($p < .01$). In the transformed color condition, there was a significant difference between the no-competition condition and the two competition conditions, which did not differ from each other ($p < .01$). We were also interested in differences between match dimensions—in particular, between the shape and transformed shape conditions and between the transformed shape and transformed color conditions—at the same level of difficulty. A Tukey's HSD ($p < .05$) revealed no significant difference between the 3 levels of the match dimension factor the no-competition condition and a significant difference between the transformed shape and transformed color conditions in the single-competition and three-competition conditions. This confirms the better results for shape analogies compared with color analogies observed by Thibaut and colleagues (2008).

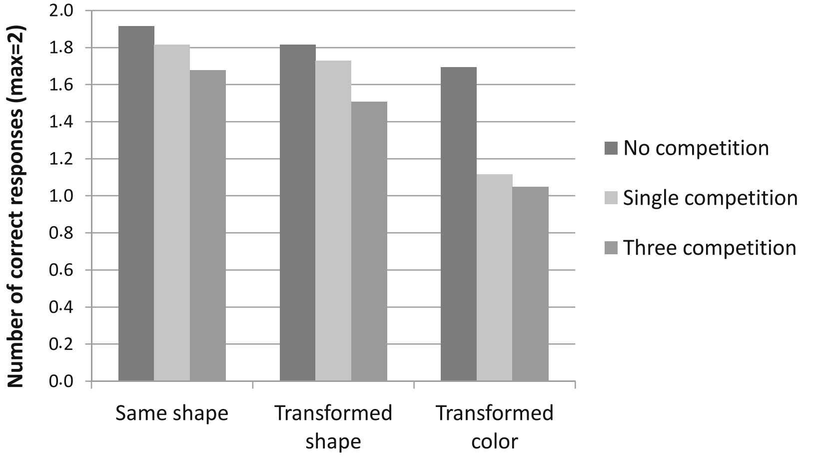

Fig. 3. Interaction between the match condition and the match dimension in Experiment 1.

Error analysis

The purpose was to analyze the distribution of the different types of errors. Fig. 4 shows that for the no-competition condition, 6- year-olds made a significant number of errors even though the solutions they chose shared no (obvious) perceptual dimension with the A, B, and C terms (in their justifications, children never claimed to have chosen a stimulus on the basis of some nonobvious relation). In the single-competition condition, we compared perceptual errors (i.e., choice of a perceptual match) and other errors (i.e., no obvious dimension match between the stimulus and the C term). We observed far more perceptual errors than other errors in all three age groups. For all three age groups, the proportion of perceptual errors differed significantly from the proportion of other errors: 6-year-olds, $\chi^2(1) = 7.99$, $p < .01$; 8-year-olds, $\chi^2(1) = 7.62$, $p < .01$; 14-year-olds, $\chi^2(1) = 5.79$, $p < .02$. In the three-competition condition, we compared the distribution of matches on the A, B, and C terms. There was also a majority of C errors for the 6-year-olds, $\chi^2(2) = 72.10$, $p < .001$; for the 8-year-olds, $\chi^2(2) = 32.33$, $p < .001$; and for the 14-year-olds, $\chi^2(2) = 25.33$, $p < .001$. This suggests that children did not consider the characteristics of the A and B terms as being part of the candidate solutions.

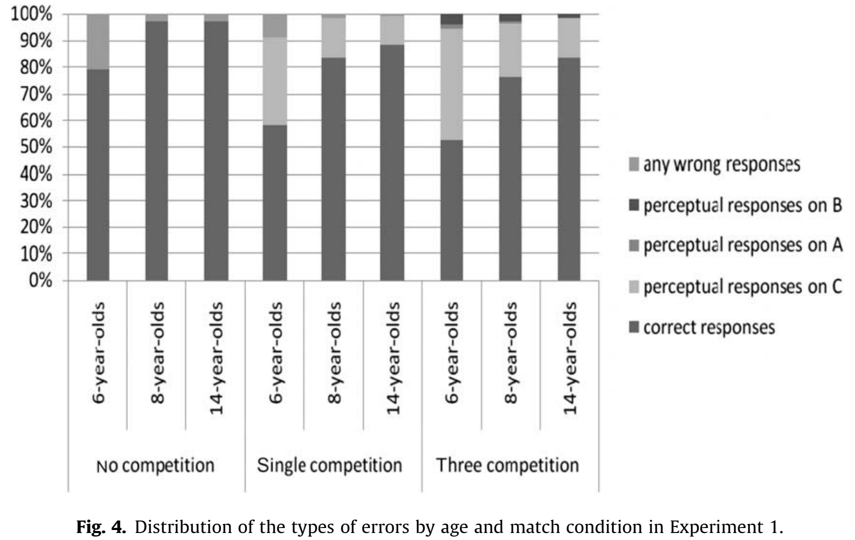

Fig. 4. Distribution of the types of errors by age and match condition in Experiment 1.

Discussion

We manipulated the number of perceptual distractors and the type of relational matching. We predicted that the addition of perceptual matches, one versus zero and three versus one, in the set of distractors would decrease children's performance. When children analyzed the set of solutions, they would have difficulty in inhibiting (i.e., ignoring) the nonanalogical perceptual solutions. Results showed that the no-competition condition was easier than the competition conditions. However, there was no significant difference in children's performance in the single-competition and three-competition conditions. The pattern of errors in the three-competition condition provides an explanation for this result in that children made a majority of errors on the C term rather than on the A or B term (see Thibaut et al., 2008). This suggests features of their processing strategies during analogy making; children considered that the solution should share a feature with the C term but not with the A or B term given that they ignored the distractor features associated with these two terms. We return to children's comparison strategies in Experiment 2 and in the General Discussion.

As in Thibaut and colleagues (2008), there was a striking difference between shape and color analogies in favor of shape analogies. Because the shape and color analogies have exactly the same formal structure, and because children are perfectly able to sort stimuli according to color, this difference cannot be attributed to a relational shift or a difference in terms of knowledge. However, because two thirds of the trials were shape trials (same shape and transformed shape), a bias toward shape could have arisen during the course of the experiment. Still, we obtained the same highly significant difference in favor of shape analogies in Thibaut and colleagues with an identical number of shape and color analogies. Another hypothesis is that shape is a priori more salient than color for children, so that they start to look at shapes rather than colors, and once they have started with this cue they use it in a rigid manner (see Gelaes & Thibaut, 2004, for a discussion of children's fixedness in categorization tasks). Or, it could be that in a competition between shape and color, children have difficulty in resisting the shape match. Thus, shape would not be a more salient solution than color, but it would be more salient as a distractor when it is in competition with color than vice versa. The absence of a significant difference between color and shape analogies in the no-competition condition would seem to support the second hypothesis. It is only when there is a competition between shape and color that shape is favored over color.

Finally, the result obtained for the no-competition condition is of interest. The 6-year-olds also made errors (20%) in this condition, where there were no obvious perceptual matches between any of the A, B, or C terms and any distractor. In the vast majority of these cases, they were unable to articulate any precise explanation for their choices. This supports the idea that they could not monitor the comparisons between the stimuli necessary to find a solution.

Experiment 2

In the current experiment, the idea was to compare children's ability to produce analogical (i.e., relational) solutions when different kinds of competing perceptual information were present. In many experiments, all perceptual information competes with the relational information to be used to find the correct (i.e., analogical) solution. We introduced perceptual noise, that is, perceptual information that had no bearing on the solution and was not in conflict with the relational solution but was designed to increase cognitive load. This noise consisted of adding random textures (e.g., hash marks, dots) to the shapes. It is noise in the sense that each stimulus has a different texture, so that no pair of stimuli has the same texture. We tried to devise textures that would be as different as possible in the sense that all textures in a set of stimuli within a trial would be perceptually different from each other. By contrast, perceptual competitors were defined as stimuli sharing an obvious perceptual value on a given dimension, as in Experiment 1 (e.g., same blue color, same square shape). In short, we wished to compare the role of obvious common perceptual dimension values with that of a source of variation—textures—that (a) had no bearing on the answer and was not in competition with any solution and (b) was perceptually different for each of the items involved in the problem and its solution.

We hypothesized that increasing the variability across stimuli by means of textures would increase the search space, thereby increasing cognitive load. This is because participants would not know a priori that textures were irrelevant and increasing variability by the inclusion of textures would increase, at least initially, the number of dimensions to process and filter out. Because younger children have less well-developed executive functions, we predicted that they would have greater difficulty in filtering out irrelevant dimensions. Thus, we should see greater difficulty in the noise case than in the no-noise case. On the other hand, if analogy making is mainly a matter of knowledge (Goswami & Brown, 1990) or of relational priming (Leech et al., 2008), once the relation between A and B has been perceived, children should be able to generalize it to C and D and should not be significantly affected by the irrelevant texture information.

In Experiment 1, we compared shape and color analogies. When the analogy was on shape, the perceptual competitors shared a perceptual value with the C term on the color dimension (and vice versa for color analogies). In the current experiment, in the shape analogies, we kept color constant across stimuli. (We did the same for the shape dimension in the color analogies.) The perceptual match was on the same dimension as the analogical match. For example, in the shape analogies, the perceptual match was a stimulus that had exactly the same shape as the C term, whereas the analogical match was a distortion of the shape of the C term.

In the current experiment, we also computed the RTs and analyzed the numbers of correct answers given. RT predictions differ from predictions concerning error rates. The RT profile depends on the strategy that children adopt to do a particular analogy. First, there should be a significant difference between the competition and no-competition conditions because in the former case participants must consider both the analogical match and the competing perceptual match *before* they choose the analogical match. This difference should occur because it takes time to analyze all potential solutions before deciding. A second possibility is that once children have found some relation between A and B, they collapse their search space to this relation and are no longer distracted by competing perceptual matches. If this were the case, there should be no significant difference between the competition conditions and the no-competition condition. This is what would be predicted by Leech and colleagues (2008). A third possibility is that, given that executive functioning (e.g., inhibition) develops with age, one might expect younger children to show no difference in RTs among the four conditions. Indeed, if children cannot resist a match between C and a perceptually salient stimulus, we would expect them to have a large number of perceptual match errors and no RT differences among the various conditions because they chose this solution without considering the other possible solutions.

To test these various alternatives, we developed an experiment with the following design: 3 (Age: 6- vs. 8- vs. 14-year-olds) $\times$ 2 (Dimension Match: shape vs. color analogies) $\times$ 2 (Noise: noise vs. no-noise conditions) $\times$ 2 (Competition: no-competition vs. competition conditions) with age as a between-participants factor. As in Experiment 1, the correct relation was having a similar but transformed shape (i.e., elongated or shrunk) or having a similar but transformed color (i.e., lighter or darker).

Method

Participants

A total of 60 children participated in this study. There were 20 6-year-olds (10 boys and 10 girls, mean age = 78.2 months, range = 72–83), 21 8-year-olds (8 boys and 13 girls, mean age = 100.9 - months, range = 96–108), and 19 14-year-olds (7 boys and 12 girls, mean age = 173.2 months, range = 168–180). Children were from middle-class families and were tested in France (Dijon), and French was their native language. None of the children had ever repeated a school year. There was a control group of 8 adults.

Materials

The experiment consisted of 16 experimental trials and 4 training trials. There were four conditions: "no-noise/no-competition," "no-noise/competition," "noise/no-competition," and "noise/competition" conditions, each represented by 4 trials. For the noise trials, each of the seven stimuli composing a trial (A, B, C, and the set of four possible solutions) received a texture, with the constraint being that none of the textures was identical to any of the other stimuli composing the trial. These textures were drawn in black (e.g., dots, lines, circles). The noise conditions were constructed using Adobe Illustrator CS3 software. The textures in a given trial had no perceptual property that could be used as a relational match (see Fig. 5 for an example). A pretest showed that no participant in the adult group made any analogy based on textures. By contrast, the competition stimuli shared a dimension value with the C term (as in the Experiment 1).

However, there was an important difference from the first experiment. The perceptual competition was always on the same dimension as the analogical solution. Take the competition example in Fig. 5. The analogical relation is same shape but elongated; B has the same shape as A except that it is elongated. In the set of solutions, the correct solution is the third shape. There is also a perceptual distractor, the fourth shape, that has exactly the same shape as C and that should be chosen if children's choices are based on perceptual matches. Recall that in Experiment 1, the perceptual competition was on another dimension—color for shape analogies and shape for color analogies. In the current experiment, all of the shapes for a given "shape analogy" trial have the same color. (Similarly, all of the colors for a given "color analogy" trial have an identical shape.) Fig. 5 gives an example of a shape analogy, and all of the stimuli have the same color.

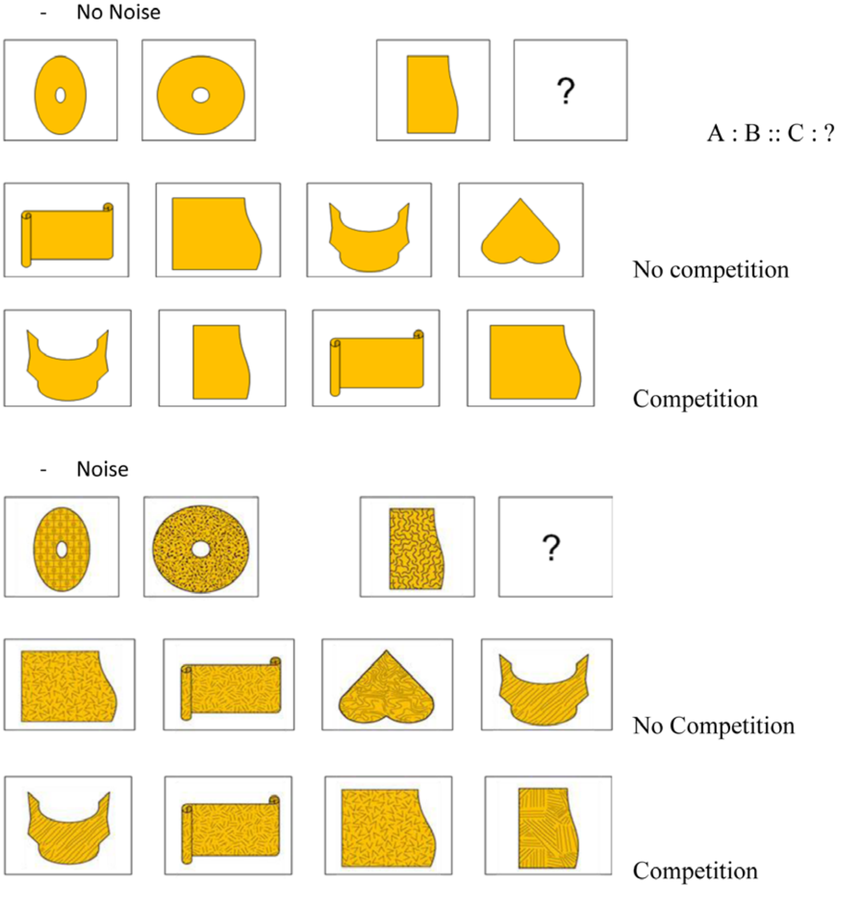

Fig. 5. Analogy display used in Experiment 2 (shape condition). (For interpretation to colors in this figure, the reader is referred to the web version of this paper.)

The experiment was programmed on E-Prime software controlling a 19-inch touch screen that was used to record children's answers and RTs.

Procedure

Children were seen individually at their school in a quiet room. Children were seated in front of the touch screen. They needed to keep their dominant hand on the desk in front of the screen, always at the same place, to keep the distance constant (30 cm) across trials and participants. Children were instructed that they would need to touch the stimulus on the screen corresponding to their choice as soon as they had found the solution. They were told that they could touch the screen only once per trial. The instructions regarding the analogy were the same as in Experiment 1. Exactly as in Experiment 1, we also checked that children realized that the C term and the analogical solution were of the same kind of shape (see Experiment 1). No feedback was given.

Each trial began when the experimenter pushed on the space bar. All seven stimuli were displayed at the same time. An RT was defined as the interval of time between the onset of stimulus presentation and the participant's response.

Results

We ran a four-way mixed ANOVA on the data with age (6- vs. 8- vs. 14-year-olds) as a between-participants factor and with match dimension (shape vs. color), match condition (no-competition vs. competition conditions), and noise (noise vs. no-noise conditions) as within-participants factors. The dependent variable was the number of correct relational matches. As in Experiment 1, we included only trials in which children indicated during posttest that the transformed analogical match was of the same type as the C term. In fact, there was no such error throughout the experiment. Because there was no main effect of match dimension (shape vs. color) and no interaction involving this factor, we removed it from the analysis. We discuss this absence of difference between the two analogy types in the General Discussion. An ANOVA revealed a significant main effect of age, $F(2, 57) = 22.95$, $p < .001$, $\eta^2 = .45$. A Tukey's HSD ($p < .05$) post hoc analysis revealed that the 14-year-olds ($M = 1.69$ of 2.00) were better than the 8-year-olds ($M = 1.33$) and 6-year-olds ($M = 0.98$). The 8-year olds were better than the 6-year-olds ($p < .01$). The analysis also revealed that the no-noise condition ($M = 1.39$ of 2.00) was significantly better than the noise condition ($M = 1.26$), $F(1, 57) = 8.08$, $p < .01$, $\eta^2 = .12$. There was also a significant effect of competition, $F(1, 57) = 93.67$, $p < .001$, $\eta^2 = .62$, with better performance for no-competition trials ($M = 1.66$ of 2.00) than for competition trials ($M = 1.00$). The Competition $\times$ Age interaction was also significant, $F(2, 57) = 4.72$,

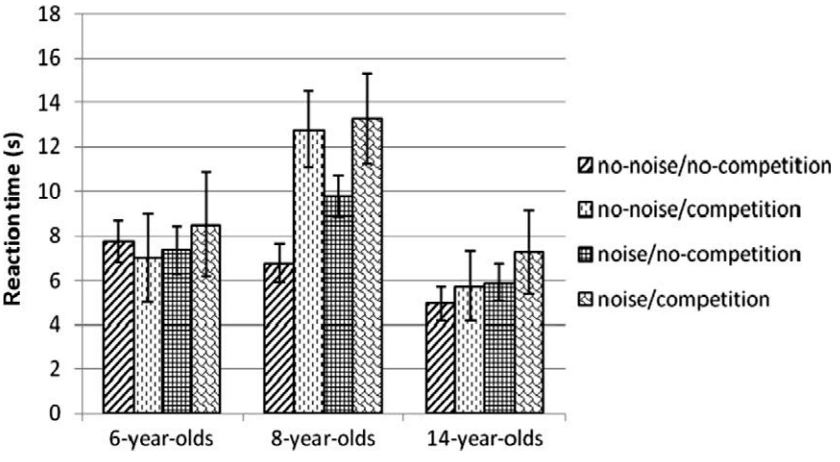

Fig. 6. Triple interaction among age, noise, and competition in Experiment 2.

$p < .02$, $\eta^2 = .14$, showing that the difference between the no-competition and competition conditions was smaller for 14-year-olds ($M = 1.87$ in the no-competition condition and $M = 1.51$ in the competition condition) than for 8-year-olds ($M = 1.74$ in the no-competition condition and $M = 0.93$ in the competition condition) and for 6-year-olds ($M = 1.37$ in the no-competition condition and $M = 0.59$ in the competition condition). There was a trend toward significance for the Age × Noise interaction, $F(2, 57) = 2.55$, $p < .087$. A Tukey's HSD ($p < .05$) revealed that the largest difference between the noise and no-noise conditions was obtained for the 8-year-olds.

We also performed an ANOVA on the RTs for correct responses. Once again, there was no main effect of match dimension (shape vs. color) and no interaction involving this factor; therefore, we removed it from the analysis. There was a main effect of age, $F(2, 44) = 4.57$, $p < .02$, $\eta^2 = .17$. A Tukey's HSD ($p < .05$) post hoc test revealed that the 8-year-olds' RTs ($M = 10.7$ s) were significantly slower than those for the 14-year-olds ($M = 6.0$ s) but did not differ significantly from those for the 6-year-olds ($M = 7.7$ s), whereas 14-year-olds' RTs did not differ significantly from 6-year-olds' RTs. There was a main effect of noise, $F(1, 44) = 5.45$, $p < .05$, $\eta^2 = .11$, with faster RTs in the no-noise condition ($M = 7.4$ s) than in the noise condition ($M = 8.6$ s). There was a main effect of competition, $F(1, 44) = 5.20$, $p < .05$, $\eta^2 = .11$, with faster RTs in the no-competition condition ($M = 6.9$ s) than in the competition condition ($M = 9.1$ s).

Most interesting, there was a significant triple interaction among age, noise, and competition, $F(2, 44) = 3.35$, $p < .05$, $\eta^2 = .13$. As shown in Fig. 6, the 6-year-olds' performance fell between the performances of the 8- and 14-year-olds. To analyze this interaction more thoroughly, we performed separate ANOVAs on each age group. Because we were interested in differences among the four conditions in each age group, the four conditions were considered as a single factor. For the 6-year-olds, the effect of condition was not significant, $F(3, 45) < 1$. For the 8-year-olds, there was a significant effect of condition, $F(3, 45) = 3.69$, $p < .02$, $\eta^2 = .20$. Interestingly, there was a significant difference between the "no-noise/no-competition" ($M = 6.8$ s) condition and the "no-noise/competition" ($M = 12.8$ s) and "noise/competition" ($M = 13.3$ s) conditions (see Fig. 6) (Tukey's HSD, $p < .05$). For the 14-year-olds, there was a significant effect of condition, $F(3, 54) = 3.62$, $p < .02$, $\eta^2 = .17$. A Tukey's HSD revealed a significant difference between the "no-noise/no-competition" ($M = 5.0$ s) and "noise/competition" ($M = 7.3$ s) conditions ($p < .02$).

To summarize, the RT profile at 6 years of age is flat, is slightly faster at 14 years of age, but is highly dependent on conflicting information at 8 years of age. This supports the hypothesis of a radical change in the way children process analogies across ages (see General Discussion).

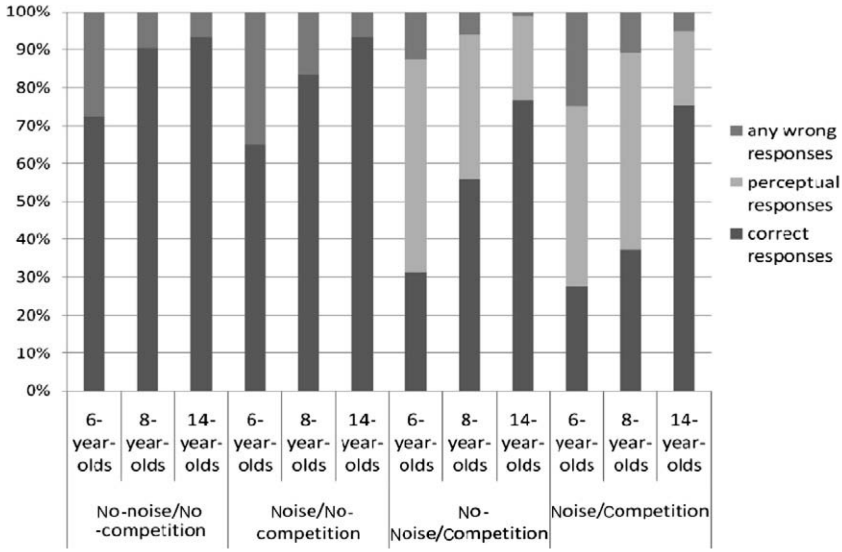

Fig. 7. Distribution of the types of errors by age and competition and noise conditions in Experiment 2.

Errors

As in Experiment 1, we analyzed the pattern of errors. We noticed a similar decrease in the number of errors with age. We also compared the three age groups in terms of the proportions of perceptual errors in the two competition conditions. (By design, there was no perceptual match in the no-competition conditions.) We compared the proportion of errors in the "no-noise/competition" condition and the "noise/competition" condition within each age group (see Fig. 7). For the 6-year-olds, a McNemar $\chi^2(1) = 7.99$, $p < .001$, revealed that there was a larger proportion of perceptual match errors (45 errors) compared with other errors (10 errors) in the "no-noise/competition" condition than in the "noise/competition" condition (38 perceptual match errors on the C term vs. 20 other errors). This was not the case for the other two age groups ($p > .05$). This is interesting because it shows that in the noise condition, younger children produced more errors other than the perceptual match errors, suggesting that introducing noise into the stimuli contributed to preventing the 6-year-olds from searching for *any* systematic matches.

Discussion

This experiment introduced a new factor that we called noise. It implemented the idea that random perceptual information (here textures) might decrease young children's performance because the noise would be harder for them to filter out than it would be for older children. We also introduced an RT measure for better characterization of children's strategies. Our results once again confirmed the negative role of perceptual competition as in Experiment 1. Interestingly, the introduction of noise also had a detrimental effect on RTs, especially for the 8-year olds. These two effects were confirmed by an analysis of the pattern of errors. Second, in contrast to the first experiment, we did not find any difference between shape and color analogies, a result that we discuss in the General Discussion. Finally, and most significant, the RTs in the second experiment provided evidence that the three age groups did not use the available information in the same way.

As before, the trials with perceptual competition were harder than the trials without competition. The Age × Competition interaction showed that the role of perceptual competition was most pronounced for the 6- and 8-year olds but was smaller for the 14-year-olds. This is consistent with older children being able to filter out irrelevant information more efficiently.

The experiment also revealed the negative effect in analogy making of what we called perceptual noise. Our results suggest that any source of variation interferes with analogy making even when it is not intended to compete systematically with some (perceptual or relational) dimension of the C term (or of the A or B term). In analyzing the Age × Noise interaction, the only significant difference between the no-noise and noise conditions was obtained for the 8-year-olds. For the 6- and 14-year-olds, there was no significant difference between these two conditions. As we see below, this result fits well with the RT data.

RT analyses further contribute to the description of the processes involved in analogy making. The major distinction is between the 6- and 8-year-olds. The 6-year-olds' data showed a flat profile; that is, there was no difference among the four conditions, suggesting that they did not allocate more processing time to conditions with noise and/or competition. Initially, we speculated that young children should have greater difficulty in controlling their searches, especially in the presence of competing information. However, the results we obtained fit well with one interpretation of executive functioning in the sense that poor executive functioning predicts younger children's difficulty in resisting competing information, whether relevant or not. In fact, children might have answered with the same speed in all of the conditions because they did not systematically compare the stimuli or they stopped as soon as they found a property that a stimulus from the solution set shared with the C term. The fact that, in the competition conditions, the majority of the answers were perceptual errors (see also Experiment 1) suggests that the 6-year-olds stopped once they found this perceptual match between C and a stimulus from the solution set. Recall that perceptual matches were easier to detect because they were identical to C on the match dimension, whereas this was not the case for the analogical match.

Despite the fact that there was no significant difference in RTs between the noise and no-noise conditions for this age group, noise nonetheless had an effect on their performance. Specifically, it affected the type of errors produced. The proportion of other errors (i.e., errors that were not driven by a common feature between the selected solution and C compared with perceptual match errors) was significantly higher in the ''noise/competition'' condition than in the ''no-noise/competition'' condition. This is consistent with the idea that in the noise condition (i.e., with more variability in the stimuli), the 6-year-olds were even less able to analyze the characteristics of the individual stimuli.

For the 8-year-olds, however, the pattern of RTs in the four conditions was radically different. Crucially, the competition conditions were much slower than the no-competition conditions. Overall, there was a hierarchy among the four conditions, with the ''no-noise/no-competition'' condition at one end of the scale and the ''noise/competition'' condition at the other end. Thus, both noise and competition influenced RTs, with competition being the more process-consuming factor. This result is consistent with the idea that the 8-year-olds extensively analyzed the set of solutions and considered both the perceptual matches and relational matches. Specifically, they considered perceptual matches as potential solutions that were later disregarded (recall that RTs were computed on correct responses). Analyzing two potential solutions before choosing one is a time-consuming process. Again, the vast majority of errors were on the perceptual match. Clearly, there is a connection between choosing the perceptual match and the difficulty of the task; the perceptual match was the dominant answer for the 8-year-olds in the ''noise/competition'' condition (an average of 0.74 correct answers out of a maximum of 2.00 and a majority of perceptual errors), whereas this was not the case in the ''no-noise/competition'' condition (an average of 1.12 correct answers out of 2.00). In short, the search for the correct solution is less obvious when it is embedded in a more highly varied perceptual background.

For the 14-year-olds, the pattern of results showed that the only significant difference in RTs was between the ''no-noise/no-competition'' condition and the ''noise/competition'' condition. One might have expected that more background noise would have required more time to parse the correct relation than when there was no background noise. However, the pattern of results that we found suggests that having high-level knowledge about a common relation is what one should be looking for in this type of problem; the 14-year-olds simply did not look at any other commonalities between C and D (common textures or common perceptual features). During the task, the 14-year-olds no doubt quickly learned that when two shapes (or two colors) appear in the base, with one shape (or color) being a transformation of the other, the correct solution should be a transformation of C.

General discussion

Our experiments go beyond prior studies in a number of ways. To begin, we eliminated semantic knowledge to the extent possible, thereby ensuring that our results were largely free of unwanted knowledge-based biases. Manipulating the number *and* nature of perceptual competitors, controlling for both the role of perceptual noise and the degree of influence of the match dimension, and recording time-to-solution RTs gave us a clearer picture of the processes involved in the development of analogy making.

In Experiment 1, we manipulated the number of perceptual competitors and the dimension on which the analogy needed to be made (color or shape). Apart from the expected age effect, results showed that conditions with perceptual competitors were more difficult than conditions with no competitors, whereas the number of perceptual competitors (one or three) did not significantly influence performance. Shape analogies were easier than color analogies. The vast majority of errors were on perceptual competitors in the competition conditions. In the three competition conditions (no-competition, single-competition, and three-competition conditions), the majority of errors were on the C term; children were much less likely to consider matches on A or B as potential solutions.

In Experiment 2, we introduced perceptual noise as a source of variation. Children were influenced both by perceptual competition and by noise. The 14- and 6-year-olds displayed the same flat RT profile; that is, for these two groups, there were no significant differences among the four conditions (except in the ''noise/competition'' condition for the 14-year-olds). Interestingly, however, the 8-year-olds were significantly slower when competitors and/or noise were introduced.

Development of the mechanisms of analogy making

How do our results constrain the way children explore the search space during an analogy task? In both experiments, we saw that children's performance was impaired when perceptual competitions were added. Experiment 1 suggests that children's search space was organized around the C term. This is consistent with both the lack of difference between the single- and three-competition conditions and the error analysis in the three-competition condition; most errors were on the perceptual match with the C term rather than on the perceptual matches with the A or B term. In other words, children generally did not seem to understand the task as a generalization of the properties of the A and B terms or the relationship between them. Rather, on most trials, children reduced the search space to commonalities with C. However, the effect of perceptual information is not limited to "obvious" perceptual matches. The increased number of errors for trials with noise (i.e., in which texture was added to the stimuli) (see Fig. 7) in the second experiment is consistent with the idea that increasing the number of dimensions also increases the task's cognitive load *even when the additional information does not introduce a direct conflict with the perceptual or relational features of the potential solutions or the C term*. Younger children's performance in the no-competition condition arguably reveals their inability to consider all solution possibilities at the same time, keeping only the best of the lot. This does not result from an intrinsic ambiguity in the stimuli themselves given that adults made no mistakes in any of the conditions and with children the numbers of such errors decreased with age. (Recall that when these errors occurred, young children either were unable to justify their choices or pointed to some characteristic(s) that could not reasonably be interpreted as being part of an analogical answer.)

We suggest a continuum of executive control in children's searching the solution space of an analogy problem, beginning with a lack of control in which a lack of inhibition plays a significant, but not exclusive, role to ever greater executive control with age. For the 6-year-olds, RTs provided by Experiment 2 and the associated error profile suggest that they did not search the entire solution space of the task. Indeed, the pattern of RTs for these children showed no significant difference among the four conditions, consistent with the idea that they searched no further than the first match that struck their fancy. This would explain their poor performance in the competition conditions and the fact that the majority of their answers were perceptual matches. Also, the significant number of errors made by the 6-year-olds that did not involve perceptual distractors and were not consistently justified suggests that these children also have difficulty in task monitoring. As a result, most of their choices are essentially random. This pattern of results is also consistent with the idea that they follow a "satisficing" strategy (Simon, 1957) in which they stop their search once they find any match with the C term.

One of the key results of this study is that the 8-year-olds' RTs in Experiment 2 could reasonably be interpreted as the result of a different way of processing conflicting information compared with younger and older children. Indeed, RTs for the 8-year-olds (for correct answers) increased in both competition conditions, suggesting that the children in this age group considered both the perceptual and analogical matches before they decided on the solutions. The 14-year-olds' pattern of RTs in Experiment 2 is also interesting. These children were faster than the other two groups, as would make sense, but their RT profile was more or less flat across all four conditions. This is consistent with the idea that they simply ignored all nonrelational choices, knowing (or quickly coming to understand) what they were looking for, that is, a relational choice. It might be that, after a number of trials, they understood that they needed to find some distorted C to comply with the overall A:B::C pattern. In an eye-tracking study of analogy making using scenes from Richland and colleagues (2006), Gordon and Moser (2007) found that participants initially focused on the actor-patient first in the source image (analogous to our A and B) and then in the target image (analogous to our C and D) before their saccades went from the actor to the distractor. Even though the stimuli were very different, this might be applied to our adolescent group; this would mean that they looked more at the A:B and C:D relations, paying little attention to any possible relation between the C item and the perceptual distractors. The slight but significant increase in RTs observed in the "noise/competition" condition suggests that it took more time to find the right solution in a more perceptually variable condition. We could predict that the 8-year-olds would produce alternate C:D and C:perceptual distractor saccades.

In short, the data suggest that there are two different strategies for the 6- and 14-year-olds. In the case of the 6-year-olds, they simply chose the first salient solution and explored no further, whereas the 14-year-olds knew the kind of answer that was being sought—namely, a relational response—and ignored competitions in seeking out this response. Only the 8-year-olds spent time exploring the solution space, analyzing each possible match.

These results provide, to the best of our knowledge, the first illustration of the connection among performance, types of errors, and RTs; thus, they provide a clearer picture of the processes involved at different moments of development in analogy making.

Shape and color analogies

The shape–color distinction would seem to imply that some dimensions might be inherently more important to analogy making than others. Because children are able to sort and categorize stimuli according to color before 6 years of age, we do not interpret the shape–color differences in Experiment 1 as being the result of either acquired knowledge (Goswami, 1992; Goswami & Brown, 1990) or a relational shift (Gentner, 1988; Gentner & Rattermann, 1991; Rattermann & Gentner, 1998). These results are compatible with the general notion of a shape bias in which children a priori pay greater attention to shapes rather than color because in many situations shape cues are more important than color cues (see Landau, Smith, & Jones, 1988).

However, the absence of RT differences between shape and color analogies in the second experiment and in the no-competition condition in the first experiment casts doubt on this general interpretation. We suggest a more specific interpretation. On the one hand, for the age groups that were considered here, color and shape are salient perceptual descriptors of the stimuli. Difficulties arise only when color comes into competition with shape. A shape match is more difficult to inhibit than a color match. Hence, the interpretation is that both dimensions are sufficiently salient to be considered, but when they come into competition, shape is more salient and, thus, more difficult to inhibit.

Relation with other work

We believe that the development of analogy making cannot be fully accounted for in terms of an accretion of world knowledge (e.g., Goswami & Brown, 1990) or via a relational shift (Rattermann & Gentner, 1998). As for world knowledge, we explicitly checked children's understanding that A and B, as well as C and D, were of the same type (similar shape or similar color). The recognition by children of this commonality was the key to finding the analogical solution. The influence of irrelevant perceptual information cannot be accounted for by knowledge accretion. We share the view of Richland and colleagues (2006) of the importance of inhibition in analogy making. We stressed the importance of the analogy term on which there is a perceptual competition, the importance of considering the nature of the dimension involved in the analogy and the way it interacts with the time course of the task, and the complex interaction between age and the way conflicting information is processed, as demonstrated by RT data and children's error profiles. Children's means of inhibiting distractor information is at the center of our explanation. Our results are also consistent with Krawczyk and colleagues (2008). These authors showed that patients with lesions in the prefrontal cortex had problems with simple analogy making each time the researchers added distractors. Similar to our results with children, Krawczyk and colleagues attributed their results to problems in inhibitory control. In a study with adults, Kroger and colleagues (2002) manipulated the number of relations to be processed and the number of irrelevant dimensions in a task similar to the Raven's Progressive Matrices task. This had an effect on both RTs and the proportion of errors. In their functional magnetic resonance imaging (fMRI) study, the authors showed that these manipulations increased activation in the parietal and dorsolateral prefrontal cortex. It would be interesting to know whether the development of these areas can account for older children's better performance in the more complex and noisy trials.

Halford and colleagues (e.g., Halford, 1992; Halford et al., 1998) analyzed analogy making in terms of relational complexity, that is, the number of related sources of variation that must be processed in parallel. Each of these has a cognitive cost that bears on the final choice of a solution and the time required to make that choice. In our view, developmental aspects of analogy making would necessarily include working memory constraints. For example, in the second experiment, the 8-year-olds' RT profiles were consistent with the idea of working memory limitations. If they tested both relational and perceptual matches, they might have made errors because they could not hold all potential solutions in working memory.

Leech and colleagues (2008) recently proposed that solving analogies of the A:B::C:? type requires first determining the (context-independent) relation, *R*, between A and B and then applying *R* to C to come up with the correct analogy. Our results show that the lion's share of the work is not in the generalization of the A:B relation but rather in the characteristics of the solution search space. For the 6-year-olds, the most difficult conditions suggest that they did not include the A:B relation in their search for D, as demonstrated by the fact that they overwhelmingly chose the perceptual distractor.

Analogy making, in our view, is a *constructive* process involving the search of a solution space that must take into consideration not just the A and B terms but *all* of the terms involved—A, B, C, and the possible choices for D. Clearly, the 6- and 8-year-olds' pattern of answers cannot be accounted for in terms of relational priming; what would the primed relations be? However, the only group that might have transferred a relation between A and B to C and D would be the 14-year-olds. Their RTs suggest that they abstracted some relation between A and B first and generalized that relation to the C:D pair. This would mean that some form of relational priming might occur in older children in situations where there is a highly salient relation between A and B and where they know that they are looking for such relations.

In conclusion, our results are consistent with, and build on, results obtained by other authors (e.g., Richland et al., 2006, on semantic analogies; Mix, 2008, on number equivalence). They all refer to the idea that perceptual properties interfere with the construction or discovery of the analogical solution. We attribute children's performance on the tasks presented in this article to the degree of cognitive load engendered by the perceptual features in competition with the relational information.

Acknowledgments

This research was supported by European Commission Grant FP6-NEST-029088. We would like to thank Lindsey Richland for providing the stimuli used in Richland and colleagues (2006).

References

Brocki, K. C., & Bohlin, G. (2004). Executive functions in children aged 6 to 13: A dimensions and developmental study. *Developmental Neuropsychology, 26*, 571–593.

Carlson, S. M., Moses, L. J., & Hix, H. R. (1998). The role of inhibitory control in young children's difficulties with deception and false belief. *Child Development, 69*, 672–691.

Chalmers, D. J., French, R. M., & Hofstadter, D. R. (1992). High-level perception, representation, and analogy: A critique of artificial intelligence methodology. *Journal of Experimental and Theoretical and Artificial Intelligence, 4*, 185–211.

Chen, Z., Sanchez, R. P., & Campbell, T. (1997). From beyond to within their grasp: The rudiments of analogical problem solving in 10- and 13-month-olds. *Developmental Psychology, 33*, 790–801.

Duncker, K. (1945). On problem solving. *Psychological Monographs, 58* [whole No. 270].

Evans, T. G. (1968). A program for the solution of a class of geometric analogy intelligence-test questions. In M. Minsky (Ed.), *Semantic information processing*. Cambridge, MA: MIT Press.

French, R. M. (1995). *The subtlety of sameness*. Cambridge, MA: MIT Press.

French, R. M. (2008). Relational priming is to analogy-making as one-ball juggling is to seven-ball juggling. *Behavioral and Brain Sciences, 31*, 386–387.

Gelaes, S., & Thibaut, J.-P. (2004). L'apprentissage de concepts chez l'enfant: Définitions stratégies et facteurs cognitifs. *L'Année Psychologique, 104*, 536–597.

Gentner, D. (1988). Metaphor as structure mapping: The relational shift. *Child Development, 59*, 47–59.

Gentner, D., & Rattermann, M. J. (1991). Language and the career of similarity. In S. A. Gelman & J. P. Byrnes (Eds.), *Perspectives on language and thought: Interrelations in development* (pp. 225–277). London: Cambridge University Press.

Gordon, P. C., & Moser, S. (2007). Insight into analogies: Evidence from eye movements. *Visual Cognition, 15*, 20–35.

Goswami (1992). *Analogical reasoning in children*. Mahwah, NJ: Erlbaum.

Goswami, U. (1998). Is relational complexity a useful metric for cognitive development? *Behavioral and Brain Sciences, 21*, 838–839.

Goswami, U., & Brown, A. L. (1990). Higher-order structure and relational reasoning: Contrasting analogical and thematic relations. *Cognition, 36*, 207–226.

Halford, G. S. (1992). Analogical reasoning and conceptual complexity in cognitive development. *Human Development, 35*, 193–217.

Halford, G. S. (1993). *Children's understanding: The development of mental models*. Hillsdale, NJ: Lawrence Erlbaum.

Halford, G. S., Wilson, W. H., & Phillips, S. (1998). Processing capacity defined by relational complexity: Implications for comparative, developmental, and cognitive psychology. *Behavioral and Brain Sciences, 21*, 803–831.

Hofstadter, D. R. (2001). Analogy as the core of cognition. In D. Gentner, K. J. Holyoak, & B. N. Kokinov (Eds.), *The analogical mind: Perspectives from cognitive science* (pp. 499–538). Cambridge, MA: MIT Press/Bradford Books.

Hofstadter, D. R., & Fluid Analogies Research Group (1995). *Fluid concepts and creative analogies*. New York: Basic Books.

Holyoak, K. J., Junn, E. N., & Billman, D. O. (1984). Development of analogical problem-solving skill. *Child Development, 55*, 2042–2055.

Krawczyk, D. C., Morrison, R. G., Viskontas, I., Holyoak, K. J., Chow, T. W., Mendez, M., et al (2008). Distraction during relational reasoning: The role of prefrontal cortex in interference control. *Neuropsychologia, 46*, 2020–2032.

Kroger, J. K., Sabb, F. W., Fales, C. L., Bookheimer, S. Y., Cohen, M. S., & Holyoak, K. J. (2002). Recruitment of anterior dorsolateral prefrontal cortex in human reasoning: A parametric study of relational complexity. *Cerebral Cortex, 12*, 477–485.

Landau, B., Smith, L., & Jones, S. (1998). The importance of shape in early lexical learning. *Cognitive Development, 3*, 299–321.

Leech, R., Mareschal, D., & Cooper, R. (2008). Analogy as relational priming: A developmental and computational perspective on the origins of a complex cognitive skill. *Behavioral and Brain Sciences, 31*, 357–414.

Mitchell, M. (1993). *Analogy making as perception*. Cambridge, MA: The MIT Press.

Mitchell, M., & Hofstadter, D. R. (1990). The emergence of understanding in a computer model of concepts and analogy-making. *Physica D, 42*, 322–334.

Mix, K. S. (2008). Children's equivalence judgments: Crossmapping effects. *Cognitive Development, 23*, 191–203.

Rattermann, M. J., & Gentner, D. (1998). More evidence for a relational shift in the development of analogy: Children's performance on a causal-mapping task. *Cognitive Development, 13*, 453–478.

Richland, L. E., Morrison, R. G., & Holyoak, K. J. (2006). Children's development of analogical reasoning: Insights from scene analogy problems. *Journal of Experimental Child Psychology, 94*, 249–273.

Simon, H. A. (1957). *Models of man: Social and rational*. New York: John Wiley.

Thibaut, J. P., French, R. M., & Vezneva, M. (2008). Analogy-making in children: The importance of processing constraints. In B. C. Love, K. McRae, & V. M. Sloutsky (Eds.), *Proceedings of the 30th annual conference of the cognitive science society* (pp. 475–480). Mahwah, NJ: Lawrence Erlbaum.

Thibaut, J.-P., & Schyns, P. G. (1995). The development of feature spaces for similarity and categorization. *Psychologica Belgica, 35*, 167–185.

Tranel, D., Anderson, S. W., & Benton, A. (1994). Development of the concept of "executive function" and its relationship to the frontal lobes. In F. Boller & H. Spinnler (Eds.). *Handbook of neuropsychology* (Vol. 9, pp. 125–148). Amsterdam: Elsevier Science.

Vosniadou, S. (1995). Analogical reasoning in cognitive development. *Metaphor and Symbol, 10*, 297–308.

Zelazo, P. D., Carter, A., Reznick, J. S., & Frye, D. (1997). Early development of executive function: A problem-solving framework. *Review of General Psychology, 1*, 198–226.