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Cognitive Load and Analogy-making in Children: Explaining an Unexpected Interaction

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Abstract

The aim of the present study is to investigate the performance of children of different ages on an analogy-making task involving semantic analogies in which there are competing semantic matches. We suggest that this can be best studied in terms of developmental changes in executive functioning. We hypothesize that the selection of the common relational structure requires the inhibition of other salient features, such as, semantically related semantic matches. Our results show that children's performance in classic A:B::C:D analogy-making tasks seems to depend crucially on the nature of the distractors and the association strength between the A and B terms, on the one hand, and the C and D terms on the other. These results agree with an analogy-making account (Richland et al., 2006) based on varying limitations in executive functioning at different ages.

Keywords: Analogy, analogy-making, development; processing constraints.

Introduction

Analogy-making is, without question, one of the most singularly important ways in which children gradually make sense of their world. 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, etc.). Further, it is well established that, while attribute-matching precedes relation-mapping in children, the preference for the latter occurs earlier or later depending on the child's familiarity with the domains involved (Gentner, 1988; Rattermann & Gentner, 1998; Goswami & Brown, 1990; etc.).

In this paper we will focus on two central lines invoked to explain child development. First, children's development can be explained in terms of the gradual increase over time of their structured knowledge of the world (Goswami & Brown, 1990; Vosniadou, 1995). According to Goswami (1992, 2001), analogical reasoning is already available in infancy and 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 separates the knowledge required to do the analogy from the structure mapping process itself. A second line of research emphasizes the role and development of cognitive factors that come under the heading of "executive functions." This latter approach claims that young children's ability to make analogies is tied to improvements in their executive functions that allow them to better handle cognitive load as they grow older. It is now well known that the so-called executive functions develop until the end of adolescence (Davidson, Amso, Anderson, and Diamond, 2006). Halford (1993) relates the ability to do analogy-making to the ability to handle the cognitive load associated with dealing with a number of relations simultaneously. More recently, Richland, Morrison, & Holyoak (2006) and Thibaut, French, Vezneva (2008) have stressed the importance of cognitive constraints in analogy-making.

In addition, analogy-making, in general, requires retrieving relations that are not immediately available in working memory when the base situation is presented. Limitations on the cognitive resources involved in processing mean that certain types of analogies, especially, those involving conflicts between perceptual and relational matches, should be harder to make. Children have more limited cognitive resources than adults and, therefore, should find these analogies more difficult to do. In their studies, Richland et al. used scene analogy problems consisting of pairs of scenes illustrating relations among objects. The authors manipulated featural distraction by varying the identity of an object in the second scene of the each pair. So, for example, if the base scene included a running cat as part of the relation (i.e., dog *chases* cat), they added to the target scene a distractor object (i.e., an object that was not part of the *chase* relation) that was either perceptually similar (a sitting cat) or dissimilar (a sandbox) to the object of the *chase* relation in the base scene. Results revealed that stimuli with the similar distractors elicited more errors than the stimuli with the dissimilar ones.

Goals of the present paper

In the what follows, we use the A:B::C:D forced-choice paradigm from Goswami and Brown (1990).

We will focus on the interaction between children's semantic knowledge and executive functions. To our knowledge, there are no studies in which the status of the semantic knowledge involved in an analogy and the executive constraints involved by the task are manipulated. We manipulate semantic knowledge by controlling the semantic associative strength between the A and B terms and between the C and D terms. The cognitive load associated with executive functioning was manipulated by varying the number of semantically related distractors in each problem. We reasoned that if children had to inhibit three distractor relations, this would engender more cognitive load than inhibiting a single distractor relation and. thereby, would lead to more errors.

In the Goswami and Brown (1990) A:B::C:D forced-choice paradigm children are shown drawings depicting A, B, C and a set of possible solutions for D. In their experiment only one of the proposed solutions was the desired analogical match. Another proposed solution was a semantically related distractor match along with the other two proposed solutions. The analogical matches, however, were also semantically related to C. In other words, in order to choose the desired analogical match, the presence of A:B was frequently not necessary at all. In their experiment, this was confirmed in a test condition in which the authors introduced C, without the A-B pair, and asked children to find a picture among a set of 4 possible solutions that went with C. As predicted, a high number of semantically related choices were selected. However, a comparable number of analogical matches were also selected (see Figure 1 in Goswami & Brown, 1990) For example, when shown a picture of a *dog*, there were four possible choices for D: *doghouse, bone, cat, (different) dog*. Here, the a priori semantic association between *dog* and *doghouse* is enough to elicit the choice of *doghouse* a high percentage of the time, whether or not this was preceded by *bird:nest*.

In light of this, we conjectured that using less semantically related analogical matches would force the children to rely more on the relation between the initial A:B pair, requiring them to move back and forth between this pair and the possible target pairs in order to find the correct mappings. This exploration, which is not necessary if C and one of the solution choices are too closely related semantically, is particularly important if mapping is seen as a process in which the structures and attributes in the base and target domain gradually become available to processing and, in particular, do not have a constant salience throughout processing (Mitchell & Hofstadter, 1990; Mitchell, 1993; French, 1995).

We, therefore, manipulated two factors — namely, the associative strengths between the A:B and C:D pairs, and the number of semantically related distractors, one or three. For example, in the analogy *bird:nest::dog:* ??, the expected solution would be a *doghouse*, with *bone* as a semantically related distractor and two unrelated distractors in the condition with one semantic distractor. The distractors *bone*, *muzzle* and *cat* were used in the condition with three semantic distractors.

We expected that the use of relational choices with less of a semantic relation to C and the presence of more semantic distractors would make the analogies harder to solve and lead to more errors because, in both cases, processing loads are increased. In the first case, where the semantic relation of the solution to C is weaker, the solution does not come immediately to mind, and, therefore, requires children to explore each of the options more carefully. Similarly, in the condition with three semantic distractors, they have to inhibit more semantic candidates than in the one-distractor case, thus leading to more errors. These predictions contrast with the standard "knowledge" view, that posits that these factors should have only marginal effects, once the child possess the semantic knowledge relating A and B, and C and D (Goswami & Brown, 1990) or the relational priming hypothesis (Leech, Mareschal, & Cooper, 2008) that equates analogy-making with a priming phenomenon, where the prime arises directly and unambiguously from A:B. This might be the case for strongly semantically related A:B pairs in which C has no influence on that relationship, but it is not, in general, the case (French, 2008).

Experiment

We used the traditional A:B::C:? analogy-making paradigm, i.e., one in which the "relational" choice is the more valid one. In this experiment, we used line drawings of existing entities, living things or artifacts. We called the first pair (A:B) the Base Pair and the (C:?) pair the Target Pair. The third stimulus (C) had 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 material was patterned after Goswami and Brown (1990).

This experiment was a 2 x 2 x 2 mixed design with Age (4-year-olds and 5-year-olds) as a between factor, Association strength (strong vs. weak) and number of semantic distractors (one or three) as within factors. The dependent variable was the number of correct relational matches.

Methods

Participants. A total of 32 children took part in this experiment: 13 4-year-old children (M = 54 months) and 19 5-year-old children (M = 67 months) participated in the experiment.

weak association						
1 semantic distractor				3 semantic distractors		
analogy problem	solution	distractors		analogy problem	solution	semantic distractors
		semantic	unrelated			
wolf : meat :: goat : ?	grass	horns	envelope, vase	child : bed :: cat : ?	basket	mouse, whiskers, claws
man : plate :: pig : ?	trough	pig's tail	key, pen	jacket : wardrobe :: ring : ?	box	finger, necklace, watch
bird : plane :: fish : ?	boat	fisherman	sofa, glasses	dress : hanger :: coat : ?	hook	scarf, sleeve, sweater
strong association						
1 semantic distractor				3 semantic distractors		
analogy problem	solution	distractors		analogy problem	solution	semantic distractors
		semantic	unrelated			
spider : web :: bee : ?	hive	flower	motorcycle, frame	cow : milk :: hen : ?	egg	comb, grain, fox
bird : nest :: dog : ?	doghouse	bone	guitar, apple	glove : hand :: shoe : ?	foot	sock, lace, sandal
train : rail :: boat : ?	water	marine	stool, hat	hen : chick :: horse : ?	foal	saddle, stable, mane

Figure 1. Set of analogy problems and distractors used in the Experiment 1

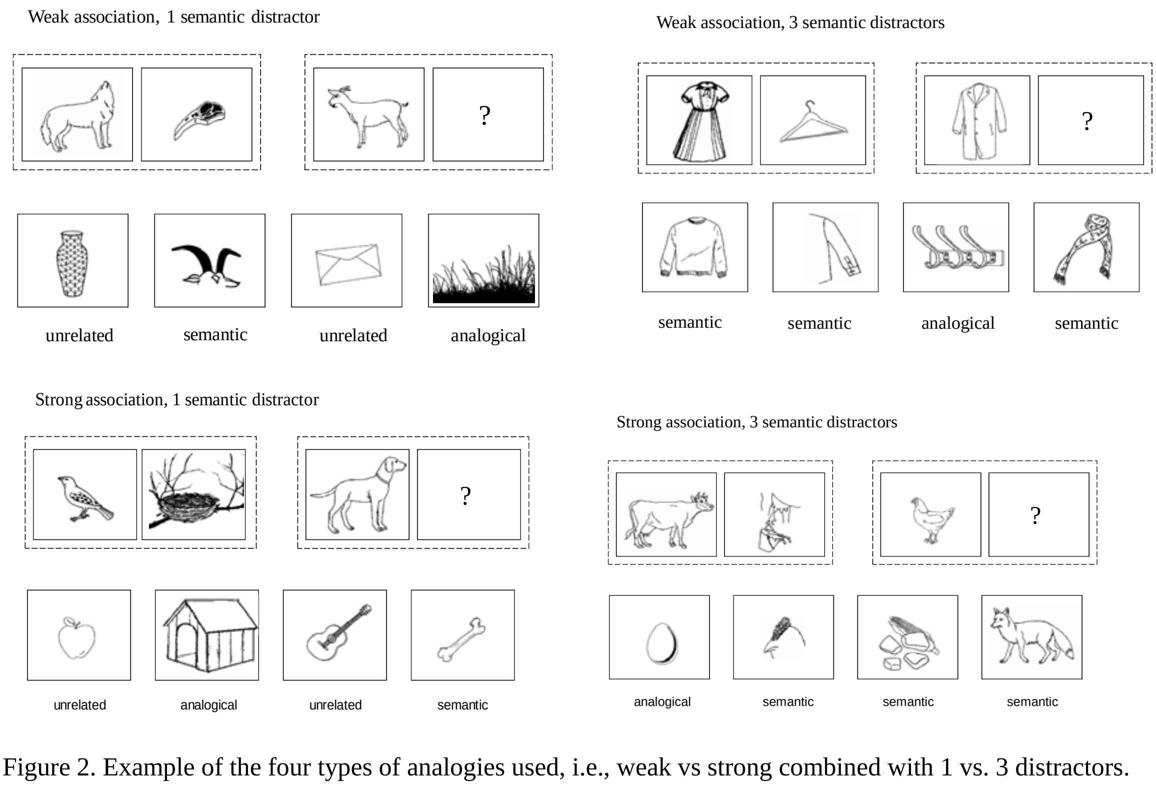

Figure 2. Example of the four types of analogies used, i.e., weak vs strong combined with 1 vs. 3 distractors.

Materials

The experiment was composed of a total of 13 trials consisting of 1 practice trial and 12 experimental trials. Each of the four conditions consisted of 3 trials. The strength of the semantic association on a 1-to-7 scale of 230 pairs of words corresponding to the pictures used in the experiment was determined empirically by 16 university students. On this basis a group of strongly associated and a group of weakly associated items were drawn up. A *t*-test was performed to ensure that the average values of the pairs of items comprising each set differed significantly (see Figure 1 for the list of items, solution and distractors, and Figure 2 for an example of each type of trial).

Procedure

The children were instructed to play a game in which they would be choosing pictures that went together. When they saw the picture cards, they were asked to identify them. If they were not able to identify an object, the experimenter told them the name of that object and explained to them how it is used. They saw the A:B pair and the C item in an array with the first two items grouped together to the left. The C item was alone on the right. Next to the C item there was a box containing a question mark for the solution item. They studied these items and, without seeing the Target items, were asked to predict what image they would put in the box with the question mark in order to complete the pattern. They were then shown the four Target items and were asked to point to the one that completed the series of items (cf. Goswami & Brown, 1990). They were asked to justify their choice for each trial: "Why did you choose this one?"

In the second part of the experiment, 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.

Results

Performance was measured as a percentage of correct responses. By "correct" we mean the choice of the item that was the valid relational (i.e., most obvious relational) match. We eliminated all the trials in which either the children did not understand the semantic relation between the A-B terms or between the C-D terms, to be sure that children did not fail because they did not have the relevant knowledge for some of these pairs.

We ran a three-way mixed ANOVA on the data with Age as a between factor and Association strength (strong vs. weak) and number of semantic distractors (one or three) as within factors. The ANOVA revealed significant main effects for two of the factors and an interaction between association strength and number of distractors. Children aged 5 performed better than 4 year-olds, F(1,30) = 4.077, p= .05, $\eta_p^2 = 0.12$ and strongly associated analogies were better understood than weakly associated analogies, F(1 ,30) = 16.76, p<.001, $\eta_p^2 = 0.36$.

The effect of number of distractors was also significant, F(1,30) = 9.41, p<.01, $\eta_p^2 = 0.24$. The interaction between association strength and number of distractors association was also significant, F(1, 30)=6.67, p<.02, $\eta_p^2 = 0.18$

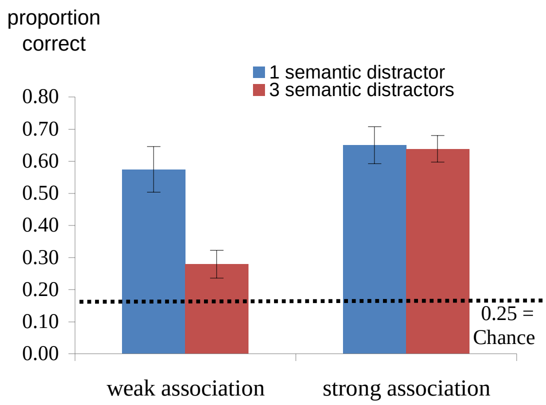

Figure 3. Interaction between Association and Number of Semantic Distractors

Discussion

The key finding is that when the items of the A:B pair (Base pair) and C:Solution (Target pair) are weakly associated (e.g., *man:plate::pig:trough)*, increasing the number of non-solution distractor items that are semantically related to C has a more deleterious effect than the same increase when the items of the A:B pair are strongly associated *(*e.g., *spider:web::bee:hive*). In other words, whether there are 1 or 3 distractors that are semantically related to C has little effect on performance if A:B and C:Solution are strongly associated. On the other hand, going from 1 to 3 distractors that are semantically related to C has a significant negative effect on performance for weakly associated Base and Target pairs.

This result makes perfect sense in the framework of a cognitive load and search space hypothesis. We would expect that difficulties arise to a greater extent when the associations are weak and when there are many semantic competitors. When the choices in the semantic search space are not dominated by a strongly associated Base pair and Target pair, the search for an appropriate answer becomes more difficult for two reasons: i) because more search is required and ii) when several semantic competitors are available during the search, they must be inhibited in order to come up with only one solution.

In short, this result fits well with the hypothesis that limitations in children's processing load capacity will affect their performance in analogy-making tasks. As would be expected, there is a small, but significant, main effect of age between the four- and five-year-old children, F(1,30) = 4.1 p = .05 (not shown in the Figure 2). Also, analogies with strongly associated items in the Base and Target pairs produced better performance than for weakly associated items in the Base and Target pairs, and finally, the effect of the number of distractors on performance was significant

The most interesting result of this experiment, however, is the interaction, showing that the difference between strong and weak associations was important when the number of distractors was high, F(1, 30) = 6.67, p<.02, $\eta_p^2 = 0.18$. This result is in contrast with Goswami and Brown's claim that children should do the analogy once they have the necessary knowledge allowing them to understand the relationships between the components that are involved in it. In the Goswami and Brown's (1990) experiment, most analogies were of the strong-association type. Our results show that this result changes significantly when the association strengths between items are weaker. Analogies of the weak-association type require the search space to be explored more broadly and lead to higher error rates. One could argue that in the strongly associated analogies the A:B pair was not necessary to find the relation between C and D. In particular, in the Weak Association/3-distractor condition children's performance did not significantly differ from chance (28%, chance = 25%). Recall that we checked to ensure that for these analogies (and for all analogies in the experiment) they understood the items and the relations between the items composing each A-B and C-D pair. One could argue that in the 1-semantic distractor condition, young children were at, or close to, chance with 57% correct answers because the non-semantic distractors were not a priori semantically related. However, young children, nonetheless, selected a significant percentage of these distractors (around 25% of errors), which suggests that they analyzed all the distractors as potential solutions.

According to Goswami and Brown's theory of necessary knowledge, increasing the number of semantic distractors or decreasing the a priori semantic association strength between the analogy components should not have dramatically lowered children's performance. But we can clearly see that their performance, in fact, did decrease significantly under these conditions. This is what one would expect, however, from a cognitive-load model.

The notion that the *semantic strength* of the associations involved in an analogy is a major factor of analogy resolution sets the present work off from the work done by Goswami and Brown (1990), Gentner and colleagues (e.g., Gentner, 1983; Gentner and Toupin, 1986; Gentner and Ratterman, 1991; Markman, 1996; etc.), Halford (1993), Mix (2007) and, most recently, Richland et al. (2006). French (1995, p. 162) discusses this problem as it relates to computational models of analogy-making. Here we have begun to explore it experimentally.

We claim that finding an analogy is a gradual constructive process whereby various alternatives are chosen based on their activation and are tested, compared with other alternatives, re-evaluated, accepted, rejected and inhibited on the way towards a solution (Hofstadter & Mitchell, 1990; Mitchell, 1993; French, 1995). In cases, typically where the associations are very strong (e.g., *cow:milk* :: *bee:?* with choices: *sting, honey, wasp, hive*), the semantically related distractors *sting, wasp,* and *hive* interfere very little. On the other hand, where the associations are weak and there are semantically related distractors, considerably more exploration and testing of the various alternatives is necessary, resulting in the far greater effect of the distractors, resulting in lower performance.

These results support the notion of the fundamental role in children's analogy-making of their developing ability to handle cognitive load. When confronted with an analogy, they, like adults, look for potential solutions or construct these solutions by testing various hypotheses (i.e., features and relations between features). When there is no obvious solution, they construct and compare different possible solutions and gradually construct appropriate representations of the objects and the relations between them necessary to do the analogy. To find a good solution, they have to inhibit other salient, but less appropriate solutions, while remaining flexible enough to replace tentative solutions with ones that appear to be better, while still be prepared to return to one's first choice later on. The point is that this process generates cognitive load associated with executive functioning. For example, it is necessary to maintain in working memory previous solutions and/or the relations and this has a cognitive cost that is crucially involved in the final choice of a solution. As mentioned above, certain authors have discussed this gradual process of the emergence of a solution (e.g., Hofstadter & Mitchell, 1990; Mitchell, 1993; French, 1995) that takes into consideration processing constraints in a theoretical framework, but the current models of child analogy-making that we are aware of do not make these constraints on processing explicit.

In conclusion, we have presented work that demonstrates the role of association strength among items making up the base and target pairs of analogies. We have shown how the amount of negative influence of semantically related distractors on the performance of children in doing analogies varies according to the association strengths of the pairs involved in the analogy. A theory of analogy-making based on mechanisms of cognitive load appears to provide a relatively straightforward explanation of these data, whereas it is hard to see how other theories that are not based on cognitive load could explain these results.

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