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Eye movements provide insight into individual differences in children's analogical reasoning strategies

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ABSTRACT

Analogical reasoning is considered a key driver of cognitive development and is a strong predictor of academic achievement. However, it is difficult for young children, who are prone to focusing on perceptual and semantic similarities among items rather than relational commonalities. For example, in a classic A:B::C:? propositional analogy task, children must inhibit attention towards items that are visually or semantically similar to C, and instead focus on finding a relational match to the A:B pair. Competing theories of reasoning development attribute improvements in children's performance to gains in either executive functioning or semantic knowledge. Here, we sought to identify key drivers of the development of analogical reasoning ability by using eye gaze patterns to infer problem-solving strategies used by six-year-old children and adults. Children had a greater tendency than adults to focus on the immediate task goal and constrain their search based on the C item. However, large individual differences existed within children, and more successful reasoners were able to maintain the broader goal in mind and constrain their search by initially focusing on the A:B pair before turning to C and the response choices. When children adopted this strategy, their attention was drawn more readily to the correct response option. Individual differences in children's reasoning ability were also related to rule-guided behavior but not to semantic knowledge. These findings suggest that both developmental improvements and individual differences in performance are driven by the use of more efficient reasoning strategies regarding which information is prioritized from the start, rather than the ability to disengage from attractive lure items.

1. Introduction

Analogical reasoning has been called the "core of cognition" (Hofstadter, 2001). This form of reasoning requires considering relations between multiple objects or representations and can be conceived as the process of mapping between a source domain and a target domain. As such, analogical reasoning is a driving force for cognitive development because it enables children to obtain and organize new information by structuring it in terms of already acquired knowledge (Gentner, 1988; Gentner & Rattermann, 1991; Goswami, 1996). Furthermore, analogical reasoning ability is a strong predictor of academic and professional achievement (Kuncel, Hezlett, & Ones, 2004). By the age of six, however, large individual differences already exist in children's analogical reasoning skills (Whitaker, Vendetti, Wendelken, & Bunge, 2017). The goal of the present study was to explore the factors that contribute to these differences and support that development of analogical reasoning.

Successful analogical reasoning requires focusing on relations rather than superficial commonalities. However, analogical reasoning can be difficult for young children who demonstrate a tendency to focus on perceptual rather than relational similarities (Gentner & Medina, 1998; Sternberg & Nigro, 1980). A prime example of this tendency comes from the relational match-to-sample task. In this task, participants are shown a sample image that represents a particular relation (e.g., two triangles to represent *same*) and are instructed to choose one of two images that goes with the sample. One of these choices might share a specific perceptual feature with the sample image (e.g., a triangle and a circle), while the other shares the same relational feature (e.g., two squares). In this task, preschool-aged children make predominantly perceptual matches, choosing the response item that contains a direct visual match with the sample, whereas older children make relational matches (Christie & Gentner, 2014). Similarly, when asked, "how is a cloud like a sponge?" and given the choice between "both can hold water" and "both are soft", the frequency with which children choose the former relational interpretation over the latter attributional interpretation increases significantly with age (Gentner, 1988). This increased attention towards relational commonalities has been termed the "relational shift" (Gentner, 1988), and it marks the beginning of

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children's ability to engage in analogical reasoning.

Two primary explanations have been put forth to explain this shift: increasing semantic knowledge (e.g., Goswami, 1996; Goswami & Brown, 1989) and improvements in inhibitory control (e.g., Morrison, Doumas, & Richland, 2010; Richland, Morrison, & Holyoak, 2006). The process of reasoning analogically by forming a mapping between the source and target domains necessarily requires some knowledge of both domains. In the example above, for example, one must know something about the function of both clouds and sponges in order to recognize that they both hold water. Although Piaget proposed that children could not successfully perform propositional analogies (e.g., A:B::C:D) until they reached for the formal operations stage (Piaget, Montangero, & Billeter, 1977), it has now been shown that even preschool-aged children can successfully solve these types of analogies if they have knowledge of the relevant relations (Goswami & Brown, 1989). However, though semantic knowledge is clearly needed in order to successfully perform these types of knowledge, gaps in knowledge alone cannot explain the systematic errors that young children make in these tasks.

Even when children have knowledge of the relevant relations in an analogy problem, it is still difficult for them to inhibit attention to perceptually or semantically similar items in favor of relationally relevant ones. For example, when solving scene analogy problems, six- to seven-year-old children perform significantly better when there is no perceptual distractor present compared to when one is included (Richland et al., 2006). Complementary findings come from a geometric propositional analogies paradigm, in which children's problem solving performance is attenuated when perceptual distractors similar to the C item are included in the response choices (Thibaut, French, & Vezneva, 2010), as well as from the pictorial propositional analogy paradigm in which children exhibit performance decrements when items semantically related to C are included among the response choices (Thibaut & French, 2016). These findings, together with findings from computational modeling and patient studies (Hummel & Holyoak, 1997; Krawczyk et al., 2008; Morrison et al., 2010; Morrison, Krawczyk, & Holyoak, 2004), as well as longitudinal studies investigating predictors of reasoning ability (Richland & Burchinal, 2013), strongly suggest that inhibitory control is a key component of successful analogical reasoning, in that children must inhibit attention towards salient distractors and instead engage their relational knowledge.

In the present study, we used eye tracking to provide insight into individual differences in analogical reasoning among six-year-old children. An advantage of using eye tracking in this context is that it provides a real-time metric of the strategies that children are engaging in while solving the task. By analyzing the order and amount of time that children spend fixating on the various items in the analogy problem, we can gain insight into how children are integrating information over the course of a trial before arriving at a solution.

A previous study that used eye tracking to investigate the development of analogical reasoning with pictorial propositional analogy problems of the form A:B::C:? found that the largest difference between the eye gaze patterns of five- and eight-year-old children compared to adults was that children tended to focus more on the C item relative to the A and B items, both at the beginning of the trial and over the course of the entire trial. (Thibaut & French, 2016). Adults, on the other hand, first fixated on the A and B items before moving onto the C item and the response options. This finding is consistent with the theory that one of the difficulties for children in a propositional analogy problem is focusing on the overarching goal (i.e., find the picture that goes with C *in the same way that A goes with B*) rather than the more immediate goal (i.e., find the picture that *goes with C*). Without initially constraining the search space by focusing on the A and B items and determining the relevant relation, distractor items that are related to C may be more difficult to inhibit if they are just as strongly associated with C as is the target. Therefore, just as inhibitory control may contribute to children's analogical reasoning performance by helping them disengage from distractor items when choosing a response, so too may goal maintenance help them to focus on the relevant task rules and employ an optimal strategy from the start.

The two strategies described above, either first focusing on the A and B items or first focusing on the C item, can be thought of as corresponding to two classic theories of analogical reasoning. The first theory is that it is optimal to engage in a project-first strategy, wherein analogies are first solved by generating the relation between the A and B items, and then applying that rule to the C item to determine the solution item, D (e.g., Doumas, Hummel, & Sandhofer, 2008; Hummel & Holyoak, 1997; Sternberg, 1977). This strategy emphasizes generating a rule that relates the A and B items in order to constrain the search space for finding the match for C, and is consistent with the eye gaze patterns found in adults by Thibaut and French (2016). The second theory is that it is optimal to adopt a semantic-constraint strategy (Chalmers, French, & Hofstadter, 1992; Thibaut, French, Missault, Gérard, & Glady, 2011). This theory rests on the assumption that because many possible relations exist between the A and B items, attention should first be focused on the C item and the response choices in order to narrow the hypothesis space. The semantic-constraint strategy therefore emphasizes an early focus on C and the response options in order to constrain the search space, and is consistent with the eye gaze patterns found in children in Thibaut and French (2016).

In a recent study investigating analogical reasoning in adults, a classification algorithm was developed that leveraged the differences in predicted eye gaze patterns between these two strategies, in addition to a structure-mapping strategy (Falkenhainer, Forbus, & Gentner, 1989; Gentner, 1983, 2010) in order to classify which strategy participants were engaging in on a trial-by-trial basis (Vendetti, Starr, Johnson, Modavi, & Bunge, 2017). The structure-mapping strategy emphasizes alignment between the A and C items and between the B item and the target. Consistent with previous findings, adults were much more likely to use the project-first strategy than either the semantic-constraint or structure-mapping strategies. Furthermore, increased usage of the project-first strategy was associated with higher overall accuracy, whereas increased usage of the semantic-constraint strategy was associated with lower overall accuracy, and use of the structure-mapping strategy was not predictive of accuracy. This suggests that the project-first strategy is optimal for performance on this analogy task.

Here, we used the same strategy classification algorithm to assess individual differences in analogical reasoning strategies in six-year-old children. Because the structure-mapping strategy was found to be unrelated to accuracy in the previous study (Vendetti et al., 2017), we focused here on the project-first and semantic-constraint strategies. We predicted that the semantic-constraint strategy would be more common at this age, but that increased usage of the project-first strategy would be associated with better performance. Analogical reasoning ability was assessed with a pictorial propositional analogy task, using pictures and relations that are familiar to young children. In contrast to previous studies that have used variants of this task with children (e.g., Thibaut & French, 2016; Wright, Matlen, Baym, Ferrer, & Bunge, 2007), this version of the task (adapted from Whitaker et al., 2017) includes both a *semantic* distractor (an item that was semantically related to the C item) and a *perceptual* distractor (an item that was perceptually similar to the C item) on each trial. This design enabled us to directly compare the relative salience of these two types of distractors, both with regards to children's visual fixations and with regards to their answer choices. We also investigated how strategy usage influenced participants' fixations on the distractor items. We predicted that children would focus less on the distractor items in trials in which they used the project-first strategy relative to the semantic-constraint strategy, particularly with regards to the perceptual and semantic distractors. In addition, we assessed children's semantic knowledge and cognitive control in separate tasks in order to determine whether these factors contribute to children's strategy usage and overall performance.