Looking Patterns during Analogical Reasoning: Generalizable or Task-Specific?

Abstract

Given the importance of developing analogical reasoning to bootstrapping children's understanding of the world, why is this ability so challenging for children? Two common mechanisms have been implicated: 1) children's inability to prioritize relational information during initial problem solving; 2) children's inability to disengage from salient distractors. Here, we use eye tracking to examine children and adults' looking patterns when solving scene analogies, allowing for differentiation between attention to relations versus to featurally salient distractors. In contrast to a recent study with propositional analogies, our data suggest prioritization of source information does not differ between adults and children, nor is it predictive of performance; however, children and adults attend differently to distractors, and this attention predicts performance. These results suggest that feature-based distraction is a key way children and adults differ during analogical reasoning, and that the analogy problem format should be taken into account when considering children's analogical reasoning.

Keywords: analogy, attention, eye tracking, reasoning, pattern recognition

Introduction

Analogical reasoning involves identifying higher order similarities in relational structure shared between representations. This form of reasoning is used in many contexts, and is predictive of academic and professional success (Richland & Burchinal, 2013). Yet, analogical reasoning proficiency develops over time: young children often struggle to notice or extract deep underlying structures from comparison opportunities (Gentner & Smith, 2013). Given the importance of developing this ability, researchers have asked why analogical reasoning problems are challenging for children. Two common explanations in the literature implicate: 1) children's inability to prioritize attending to relational information during initial problem solving, or 2) children's inability to disengage from featurally salient distractors.

Prioritization of Relational Information

One explanation for children's difficulty with analogical reasoning problems is that they fail to attend to relational information that is crucial for correctly solving problems. Much of this work has used propositional analogies, in the format A:B::C:D. In these analogies, participants select from four choices a D item that is relationally similar to the C item in the same way that A and B are similar. For example, if A and B are both triangles, with B being a stretched version of A, and C is a square, the correct choice for D would be a stretched square. A featural distractor in the response choices might be a diamond of the same color as the square – color being a salient perceptual feature that could distract from the deeper, structural relation between C and the stretched square.

From eye tracking work, we know that adults generally attend to the A:B pair before fixating on C and the response choices, showing that they can maintain the overarching goal (i.e. find the picture that goes with C in the same way that A goes with B) (Starr, Vendetti, & Bunge, 2018). In contrast, 5- and 6-year-old children ignore the A:B items, and focus their attention on C and the response choices (Glady, French, & Thibaut, 2017; Thibaut & French, 2016). This suggests that children do not extract relational information before considering response options, instead focusing on the immediate task goal (i.e. find the picture that goes with C).

In support of this idea, using linear discriminant analysis, French and Thibaut (2014) found that children's visual attention during the first third of the trial can predict with 64% accuracy whether or not the problem would be answered correctly. This is especially true if attention is focused on the A:B pair. Glady and colleagues (2017) have shown that guiding children's attention to the A:B pair during initial problem solving significantly improved children's performance.

Featurally Salient Distractors

While attention during the task may be important, an alternative explanation for children developing proficiency on analogy problems emphasizes the effect of featurally salient distractors. In many situations that require analogical reasoning, the visual scene is complex. Although a higher order relational structure is present, children are more likely to make judgments based on mere appearance or surface-level similarities between representations – attending to items that are perceptually or semantically related to the item in question, rather than structurally related. Young children are particularly susceptible to this type of error, tending to shift from more object-based similarity matching to more relational reasoning over time, defined as the *relational shift* (Gentner, 1988). Adults also appear to make relational shifts when reasoning about information for which they have low knowledge, yet children tend to make featural errors even when reasoning about relations that are familiar (Richland, Morrison & Holyoak, 2006). This finding has led researchers to suggest that the inability to disregard salient featural information in favor of relational information may be, at least in part, attributed to still developing executive function (EF) resources, and that gains in EF allow children to increasingly manipulate complex relations in working memory and direct attention toward relevant aspects of an analogy (Richland et al., 2006; Simms, Frausel & Richland, 2018).

Behaviorally, this explanation has been supported using a variety of analogical reasoning tasks (i.e. scene analogy and propositional analogy paradigms). For example, Richland and colleagues (2006) asked children to identify relational similarities between two scenes (e.g. a source and target scene), while ignoring items with featural similarities. In their task, the goal was to identify something in a target scene that corresponded relationally to a prompted item in a source scene. Importantly, a featural distractor, an item in the target scene that was not incorporated in the relation of focus and had great surface similarity to the prompted item in a source scene, was sometimes present in the target scene (Richland et al., 2006). For example, a pair of scenes might depict a relation of a dog chasing a cat (source scene) and a man chasing a woman (target scene). If the dog was prompted, the correct choice would be the man and the incorrect featural choice would be a perceptually similar dog in the target scene. For children ages 3-4, the perceptually similar match was an effective featural distractor, such that accuracy for the problems with distractors was 15% less than that for the problems without distractors. Individual differences in children's EF (working memory in particular) explained these patterns of performance (Simms et al., 2018). Further, these behavioral findings have been complemented by modeling work: Simulations in the LISA computational model of analogy (Hummel & Holyoak, 1997, 2003) suggest that changes in inhibition levels, along with relational knowledge accretion, account for young children's difficulty when reasoning analogically (Morrison, Doumas, & Richland, 2011; see also Doumas, Morrison, & Richland, 2018). Using the same task, the model replicates the experimental findings of Richland and colleagues (2006), such that the model was more likely to choose a featurally similar distractor object than an analogically correct choice.

Thibaut and colleagues (2010) demonstrated a similar effect of featural distractors using propositional analogies. Similar to scene analogy paradigms, correct responses require inhibition of salient features and a focus on common relational structure. As with scene analogies, children were more prone to errors when featural distractors were present. Indeed, later work using eye tracking revealed a negative association between the amount of time looking to a distractor and performance, such that the more time children spent looking at the distractor the worse they performed (Thibaut & French, 2016).

Distractor versus Prioritization

Whereas the majority of previous literature has considered these two mechanisms separately, Starr and colleagues (2018) examined both how looking to featural distractors and focusing on source relational information affected children's ability to solve propositional analogies. They argued that children's poor performance was due to an inability to prioritize attending to the A:B relation when initially processing an analogy, rather than an inability to disengage from perceptual lures. What is unknown is whether this finding is unique to propositional analogies, or consistent across all analogy types.

Current Study

Here, we examined visual attention while children and adults solved scene analogy problems similar to those used by Richland and colleagues (2006). If the main factor underlying children's poor performance on scene analogy problems is their non adult-like looking patterns (characterized in propositional analogies as a prioritization of relational information – A:B pair – during early problem solving) we should find that adults show greater attention to the source scene and key relationship than children, especially early in problem solving. We should also find that attending to the source relation predicts performance. Indeed, we already know that adults initially focus on the relations within a source scene – prioritizing the existing structural relation before considering the target scene (Gordon & Moser, 2007). However, if we do not find this difference in visual attention between adults and children, this would suggest that whereas adults may have a systematic approach to solving all analogy problems, the format of the problem may have a strong influence on how children solve these problems. In this case, Starr and colleagues' findings would be specific to propositional analogy problems.

The scene analogy task also allows us to measure looking to the featural distractor, determining whether children's looking patterns appear similar to or systematically different from adults'. Thus we will examine both looking to the source relation, as well as attention to featural distractors to assess which of these attentional mechanisms best explain children's developmental trajectory in solving scene analogies.

Methods

Participants

Data from 57 4- and 5-year-old children (29 females, M_{age} = 4.88, SD_{age} = 0.47) and 45 adults (37 females, M_{age} = 19.45, SD_{age} = 0.99) were analyzed for the present study[1]. Participants represented a diverse sample from a large metropolitan city. Children were recruited from schools and participated individually in one experimental session during a regular school day. Children were compensated with stickers and a certificate noting their participation in a research study. Adults were recruited from a participant pool at a university and participated individually in a lab setting.

Materials

Stimuli. Participants were shown scene analogies adapted from Richland et al. (2006). Each stimulus included a pair of scenes presented simultaneously on a *15-inch* Dell laptop. Pairs of scenes depicted one of two *relation categories* (i.e. chasing or reading) occurring between items (i.e. animals or people) within the scenes. Source scenes contained five

[1] Data from 57 children and 60 adults was collected. Although all children were included in analyses, a subset of data from particular timepoints were excluded from 8 children based on insufficient usable eye tracking data. Five adult participants were excluded for having lacking sufficient eye tracking data. For adult participants to be included in the sample, they must have > 75% accuracy. This was to ensure that we had a measure of successful, mature visual attention patterns. Ten adult participants were excluded for having < 75% accuracy across trials.

items: the two items within the relation that participants were to attend to, and three additional items (i.e., neutral inanimate objects). Target scenes also contained 5 items: the two items within the relation, two additional items, and a featural distractor.

Figure 1a. shows an example of a "*chasing"* relation depicted in both a source and a target scene. The source scene on the left shows a tiger *chasing* a woman (items within the chasing relation), and the corresponding target scene on the right side shows a lion *chasing* a horse (items within the chasing relation). Target scenes also contained a featural distractor that was featurally similar to the prompted source-scene item. In Figure 1a., the tiger in the target scene serves as the distractor because the tiger is prompted (i.e. circled) in the source scene. To maintain the same number of items across scenes, additional items were included. These items were *neutral*, meaning they were not involved in the chasing relations and were not the distractor (in Figure 1a, source scene: dog house, jeep, and plant, target scene: barn and soccer ball). Importantly, the distractor is never involved in the relation within the scene. Distractors were centrally located, increasing the likelihood that participants would notice them.

Figure 1b. shows an example of a "*reading"* relation in both a source and a target scene. Items depicting the reading relation were oriented towards each other with one character reading to the other character. In all source scenes, one of the two items within the relation of chasing or reading was prompted with a circle. The directionality of relations within a pair of scenes was reversed to avoid children making choices based on spatial location alone. For example, in Figure 1a., if chasing is depicted between characters to the left in a source scene, the chasing would then be depicted to the right in the target scene.

Eye Tracker. Eye tracking data were collected via corneal reflection using a TobiiPro X3-120 remote eye tracker affixed to a *15-inch* Dell laptop. Tobii software was used to perform a 5-point calibration procedure using standard animation blue dots. This step was followed by the collection and integration of gaze data with the presented instructional videos (described below) using Tobii Studio (Tobii Technology, Sweden). All gaze data was extracted from Tobii Studio Software for each participant.

Procedure

For the purpose of the present question, we considered a subsection of data from a longer study: eye tracking data during which children and adults visually attended to scene analogy problems without any training on how to solve them. For children, the data came from 12 pretest problems (6 chasing; 6 reading), after which children received training on how to solve scene analogies and completed 12 posttest problems. For adults, the data came from 24 problems (12 chasing; 12 reading). Items included in a child's pretest and posttest were counterbalanced, and all items were shown to adults.

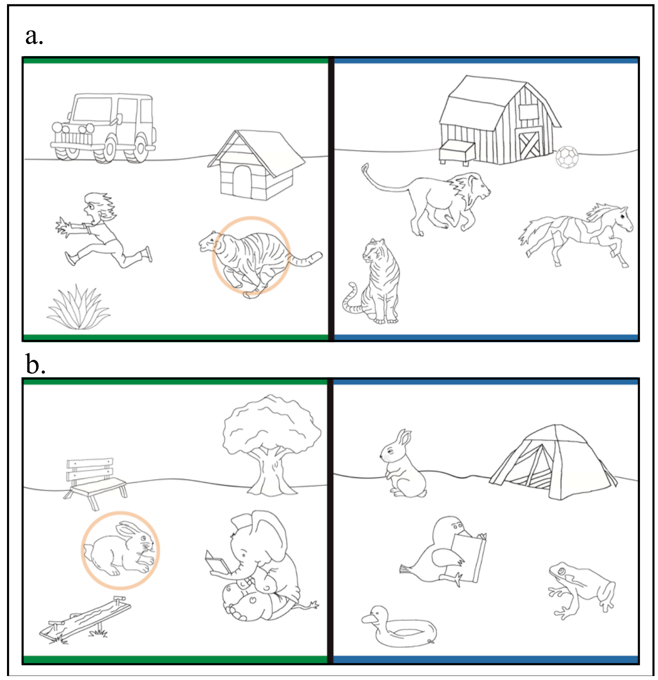

Figure 1. a. Example trial of *chasing* relation category. b. Example trial of *reading* relation category.

Introduction to Task and Calibration. Participants were told they were going to play a picture game and shown one example trial, orienting them to the layout of test trials (i.e., two pictures with different colored borders), and their task (i.e., that for each set of scenes their job was to figure out the pattern in the pictures). The experimenter described the chasing relation and asked the participant to solve the relation. For children, the explanation was repeated until they chose the correct item. This introduction ensured that when children incorrectly answered a trial, it was not because of a misunderstanding about the goal of the task.

Next, calibration on the eye tracker was completed: participants were seated approximately 40 cm in front of the laptop, familiarized with the eye tracker, and told it was important to remain still throughout the session.

Task. Participants completed a set of scene analogies while their visual attention was monitored. Participants were instructed to respond verbally to "*Which thing in the picture with the blue edges is in the same part of the pattern as the circled thing in the picture with the green edges?*". The task was self-paced, but if no response was given after a few seconds, the experimenter re-prompted. Responses were recorded for each trial.

Results

Areas of interest (AOIs) were generated for the items within the scene pairs using Tobii Studio (i.e. each trial had 10 AOIs, 5 in each scene). The remaining spaces outside of these AOIs were collapsed into an "Other" AOI. For analyses, we considered visual attention to 1) the source relation (comprised of two relational items and analogous to the A:B items in propositional analogies) and 2) the distractor (analogous to a choice item in propositional analogies). Data were extracted and processed so that the AOI a participant fixated could be determined at 8 msec intervals across the entire length of each problem. Proportion of time spent looking to each AOI was calculated using the total gaze duration of a given trial (e.g., 1000 msec), and the amount of time spent looking at a given AOI during a particular trial. All analyses considered visual attention patterns and accuracy at the trial level, not aggregated across trials for a given participant.

Because prior work (Starr et al., 2018; French & Thibaut, 2014) suggests visual attention during initial solving has the most predictive power for whether a participant will arrive at the correct answer, we consider proportion of looking to these AOIs across the entire trial, as well as proportion of looking during an initial segment of each problem. In prior work, participants had set time limits for solving problems, thus, researchers could consider a set amount of time (e.g., the first third or fourth of a trial) when examining attention at the beginning of problem solving. Here, we used a self-paced design, which resulted in variability of trial length both across and within participants. Therefore, we considered the first 5 fixations of each trial as the first interval of problem solving.

Prioritization of Relational Information

Our primary goal was to establish whether visual attention to the source relation during scene analogy problems differed between age groups in the same way as for propositional analogies. Figure 2 shows the proportion of visual attention allocated to AOIs for both children and adults. In contrast to previous work using propositional analogies, both children and adults attended to the source relation about one-third of the time, across the entire solution time (adults: $M = 0.34$, $SD = 0.05$; children: $M = 0.33$, $SD = 0.66$). A generalized linear model supported the interpretation that attention to the source relation did not differ by age group ($\beta = -0.01$, $SE = 0.01$, $t = -0.39$, $p = 0.70$). Focusing just on initial solution time revealed that a higher proportion of looking to these items occurred when participants first viewed these problems than across the entire trial: adults spend nearly half of early problem-solving time focused on this relation ($M = 0.52$, $SD = 0.10$), and children allocated just under half of their attention to these items ($M = 0.44$, $SD = 0.18$). Again, there was no significant difference in this looking pattern between groups ($\beta = 0.00$, SE = 0.01, $t = 0.24$, $p = 0.81$).

In order to make conclusions about whether looking to the source relation supports successful reasoning, we must assess the relation between performance and visual attention patterns. Unsurprisingly, children performed poorly on scene analogies, answering less than one-third of the problems correctly ($M = 0.30$, $SD = 0.26$), whereas adults were much more accurate ($M = 0.92$, $SD = 0.06$). Because adults performed nearly at ceiling, we only assess whether looking patterns predict accuracy for child participants.

Binomial generalized linear models, with accuracy on each problem (0, 1) as the dependent measure, were used to determine whether looking to source relation is predictive of behavioral performance. In contrast to prior work, we found no relation between performance and looking to the source relation across the entire trial (β = 0.30, SE = 0.82, t = 0.34, p = 0.71), or during initial problem solving (β = 0.05, SE = 0.33, t = 0.16, p = 0.87) and learning. Overall, these results challenge previous work suggesting that children's lower performance on analogy problems can be explained by failures to attend adequately to the source relationship.

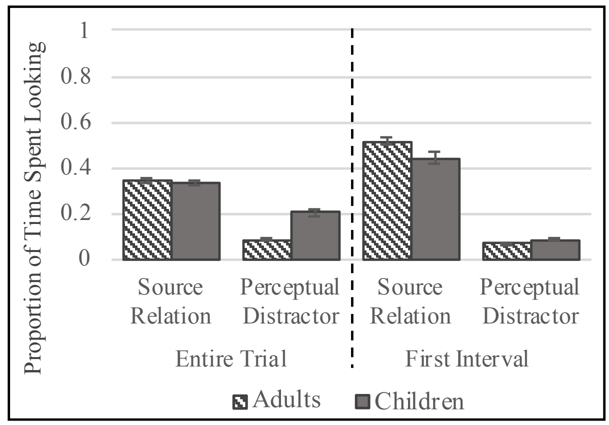

Figure 2. Proportion of time looking to source relations and distractors across entire trials and the first interval of trials.

Featurally Salient Distractors

When children and adults were not looking at the source relation, how did they allocate their attention? In line with previous work assessing children's visual attention during analogical reasoning, children spent roughly 10% percent more of their time looking to featural distractors ($M = 0.20$, $SD = 0.10$) as compared to adults ($M = 0.09$, $SD = 0.02$) across the entire problem-solving time. A generalized linear model indicated that children spend reliably more time looking towards the distractor than did adults ($\beta = 0.09$, $SE = 0.01$, $t = 6.31$, $p < .001$). However, during initial problem solving, both children and adults spent less than 10% of their time looking to the distractor (adults: $M = 0.07$, $SD = 0.03$; children: $M = 0.09$; $SD = 0.06$). A generalized linear model supported a lack of difference between age groups ($\beta = -0.05$, $SE = 0.03$, $t = -1.75$, $p = 0.08$). This indicates that, at first, children and adults explore the distractor equally, but children continue assessing the distractor throughout the trial.

Finally, we asked whether behavioral accuracy was predicted by looking to the distractor. Interestingly, in line with previous work, children performed better if they spent less time looking to the distractor across the entire problem-solving time ($\beta = -9.21$, $SE = 1.29$, $t = -7.16$, $p < .001$). However, when considering initial looking times only, there was no relation between looking to the distractor and performance ($\beta = 0.88$, $SE = 0.62$, $t = 1.41$, $p = 0.16$), suggesting that initial attention to the scenes was not the key differentiating period.

Discussion

While previous work seems to be at a consensus about the differences between mature and immature visual attention patterns while solving propositional analogies, the current study was conducted to see if these patterns hold when children and adults solve scene analogies, which are arguably more similar to real world analogies. Specifically, previous work shows that when solving propositional analogies, children look less to the source relation (A:B) than adults, and that prioritizing attention to relational information early in analogical problem solving is predictive of later accuracy (Glady et al., 2017; Starr et al., 2018; Thibaut & French, 2016). Here, we do not find differences in patterns of attention to the source relation when solving scene analogies between children and adults, neither in their initial attention nor in the full problem-solving period. Furthermore, we do not find that children's attention to relational information is predictive of their performance, even though we replicate the pattern that children perform significantly worse than adults. We do, however, find that attention to the featural distractor predicted accuracy in children. Together, these results suggest the format of the problem influences attentional patterns and that prioritization of relational information is not always critical for successful problem solving across all analogy paradigms.

While both propositional and scene analogies require processing relational information in order to arrive at a correct solution, their structures differ significantly. This difference in structure may account for why children approach these problems in different ways. In analogies of A:B::C:D format, children who are not skilled at analogical reasoning seem to overlook the relational information contained in the A:B pair, and focus on 'C' and the response options, because they interpret the task as 'match 'C' to something' and treat A:B as irrelevant. In the example used previously from Thibaut & French (2016), children might ignore that 'shape' is the relational structure, such that B is a stretched version of A, and be more likely to pick an option that is similar to C on another dimension, such as 'color'. It seems that the salience of the A:B pair is not great enough to warrant attention from those children who do not understand the task goal. In contrast, in a scene analogy, children's visual attention is still drawn to the source relation initially, perhaps due to the circled item. Based on our results, the salience of the circled item draws both children and adults' attention equally at first, but unlike adults, children less often utilized that information to correctly solve the problem. Furthermore, the presence of a distractor lowered children's performance and drew children's attention. While looking to the source relation is obligatory for children and adults because of the circled item's salience, this looking pattern does not uniformly result in successful analogical reasoning.

Previous work has consistently demonstrated that adults prioritize relational information during initial problem solving, characterized by looking to the source relation (Gordon & Moser, 2007) or the A:B pair (Starr et al., 2018; Thibaut & French, 2016). Perhaps because adults understand that they need to identify the deeper structure in these problems, and therefore, are more proficient analogical reasoners, they are not restricted by the structure of the problem. Adults can organize their visual search in a particular way despite analogy format, whereas children's visual search during analogical reasoning is strongly influenced by problem structure, and, as will be discussed next, the presence of a featural distractor.

The secondary goal of this work was to ask if looking patterns to featural distractors are comparable between scene analogies and propositional analogies (Thibaut et al., 2010; Thibaut & French, 2016). Across the entire problem-solving episode, children allocated more of their attention to the distractor than adults, and this was negatively related to behavioral performance. This corroborates previous work using propositional analogies (Thibaut & French, 2016). However, when we only considered the first interval of problem-solving time, children and adults allocated an equal amount of time to the distractor, and this was *not* predictive of performance. This differs from previous work that has stressed the importance of initial looking patterns for predicting accuracy.

Based on these results, we can suggest that when solving scene analogies, adults and children both consider the distractor, but children continue their examination of the distractor across the entire trial. It is this continued focus on the distractor that leads to poor behavioral performance – initial consideration may be indicative of children and adults processing the items that appear in the source and target scenes before working to solve the problem.

Overall, incorporating our findings about children and adult's visual attention across the problem-solving process and during initial solving, and attention towards the source relation and distractor, we can conclude that children and adults organize their visual search in different ways when solving analogical reasoning problems: In processing analogies, adults begin by identifying the relational information necessary to understand the structure of the analogy. In contrast, children have more disorganized looking patterns, such that their visual search is dependent upon analogy format, rather than the overarching goal to identify relational structure. The consistent effect of featural distractors on children's visual attention, across analogy formats, lends further support for the conclusion that children have inefficient looking patterns. While consistently looking to distractors could be considered an 'organized looking pattern' because they perform this behavior somewhat reliably, in this case, it demonstrates children's difficulty attending to underlying relational structure. This conclusion is in line with the work of Glady and colleagues (2010), who found a clear difference between adults and children's visual strategies when solving analogy problems, such that adults have more organized search patterns (Glady, Thibaut, & French, 2010).

Although our work adds an important piece to understanding the development of analogical reasoning ability, it should be noted that one limitation of this work lies in the restricted comparisons that can be made between propositional and scene analogies. Specifically, previous analogical reasoning research has made strong conclusions about the differences between age groups in terms of looking to the C item in propositional analogies (A:B::C:D), such that children look more to the C item earlier in the problem solving process and focus their search around C, whereas adults will search in a more organized way by first examining the A:B pair and then looking at the C item and the possible answers (Starr et al., 2018; Thibaut & French, 2016). Unfortunately, there is not a functionally comparable item to C in a scene analogy. Items C and D are already in relation with one another in a scene analogy, whereas D must be chosen from multiple options by the participant in a propositional analogy. Therefore, in this study, we cannot make conclusions about looking to the C item. This, again, speaks to the structural difference between propositional analogies and scene analogies.

Overall, our results suggest that while there are some generalizable differences between how adults and children process analogies regardless of their format, there are other aspects of how attention is allocated that are dependent upon analogy type. These results allow us to resolve inconsistencies in previous work by identifying exactly how children's visual attention differs across analogy formats. Gaining a better understanding about these differences across the domain of analogical reasoning will better elucidate the attentional mechanisms underlying learning in this domain and inform teaching techniques. Determining how children view analogy problems will help us understand what underlies this behavioral ability in children and adults, and could lead to evidence-based practices for teaching analogical reasoning through guided looking. This work, and future work in this field, can begin to inform practical instructional techniques by helping educators design instruction that reaches diverse classrooms of learners, as they struggle to develop this difficult, yet important ability: analogical reasoning.

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