

Working Memory and Inhibition as Constraints on Children's Development of Analogical Reasoning

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Abstract

We developed a picture-mapping task (Richland Picture Analogies, RPA) to examine the roles of inhibition and working-memory load on children's development of analogical reasoning. Children of ages 3-4, 6-8, and 13-14 were instructed to use relational correspondences between source and target pictures to select the target object corresponding most directly to a specified source object. The study examined age trends in children's proficiency with analogical reasoning. Relational complexity and perceptual distraction were manipulated to investigate how maturational constraints interact with each other and with age. Results indicate that children's development of the capacity to reason analogically interacts with increases in working-memory capacity and inhibitory control.

Children's higher-order reasoning skills are central to their ability to transfer knowledge from an initial learning context to future environments. This process enables children to understand novel situations and contexts, to build on their everyday learning experiences and to develop a flexible body of knowledge (Gentner, Holyoak & Kokinov, 2001; Gentner & Rattermann, 1991; Holyoak, Junn & Billman, 1984). Following Gentner (1983), analogy is defined as a conceptual strategy in which a source object is represented as similar to a target object, and correspondences are mapped between the two analogs. Although there is wide agreement that this conceptual process is central to children's everyday learning, the mechanisms underlying and constraining the development of analogical reasoning are not yet well understood.

The process of constructing an analogy requires a reasoner to represent source and target analogs, maintain both representations in working memory (WM; Hummel & Holyoak, 1997, 2003), and construct a mapping between elements of the source and target based upon correspondences between relations in each (Gentner, 1983; Holyoak & Thagard, 1989). Critically, the relational correspondences may compete with more superficial perceptual or semantic similarities between individual objects, requiring inhibitory control when relational and more superficial responses conflict (Gentner & Toupin, 1986; Morrison et al., 2004; Viskontas et al., in press).

Proposed Developmental Mechanisms

Researchers have proposed three developmental mechanisms to explain age-related changes in children's performance on analogical reasoning tasks: increased domain knowledge, a relational shift, and increased WM capacity for manipulating relations.

Goswami (1992, 2001) proposed domain knowledge as the primary mechanism underlying developmental changes in analogical reasoning. According to her relational primacy hypothesis, analogical reasoning is available as a capacity from early infancy, but children's analogical performance increases with age due to increased knowledge about relevant relations. This hypothesis was developed in reaction to Piagetian studies suggesting that children are unable to reason analogically prior to achieving formal operations, approximately at age 13 or 14 (Piaget, Montangero & Billeter, 1977). Piaget's tasks frequently involved uncommon relations, such as "steering mechanism", which would likely have been unfamiliar to younger children. In contrast, research has since shown children can reason analogically at much

younger ages (e.g. Gentner 1977, Holyoak et al., 1984). Goswami and Brown (1989) argued that children as young as 3 years old were successful on analogical reasoning tasks when they demonstrated knowledge about the relevant relations. Goswami and Brown presented children with complex versions of analogy tasks in which two physical, causal relations (e.g., cutting and wetting) were imposed on a source object “a” to become source object “b.” Children were required to map on the basis of these relations to complete an analogy of the form a:b::c:d. The investigators found that children were fairly competent on these problems with 2 relational changes when they showed knowledge of the relations.

These data provided some evidence that domain knowledge is related to successful analogical reasoning, but the methodology of this study has been criticized.

Rattermann and Gentner (1998) found that when a substantial perceptual distractor was included in the Goswami and Brown stimuli, children younger than age five were likely to select a perceptual match in spite of knowledge of the relations and explicit analogy instructions. Gentner and Rattermann (1991; Rattermann & Gentner, 1998) posited that a “relational shift” occurs between the ages of four and five. Before the relational shift, they argue that children primarily attend to perceptual similarity and will reason on the basis of perceptual features if available. Following the relational shift, children can and do reason on the basis of relational features even when faced with perceptual distractors. The authors suggest that domain knowledge is integral to the relational shift, though the mechanism is not explicitly postulated.

An alternative explanation for the relational shift is that children younger than age five were unable to inhibit their responses to perceptual similarity, although they were aware that the task required attention to relational similarity. It is well-established that children’s inhibition capacity develops with age (Diamond, Kirkham & Amso, 2002), and follows similar age-related patterns as does analogical reasoning. Accordingly, development of children’s inhibitory capacity, one aspect of the human working memory system, may underlie children’s patterns of success and failure on analogical reasoning tasks.

Finally, WM constraints have been proposed to explain developmental change in analogical reasoning. In particular, relational complexity has been argued to constrain children’s performance on analogical reasoning tasks (Halford, 1993). Two primary definitions of relational complexity have been advanced. Zelazo et al, (2003, 1998; Frye & Zelazo, 1998; Frye et al., 1996) define complexity as the number of hierarchical rules that must be maintained in working memory in order to accomplish a task, a view proposed as Cognitive Complexity and Control (CCC) theory. For example, in the Dimensional Change Card Sort (DCCS) task, children were asked to follow a rule to sort by color (e.g., “if red ... here” and “if blue ... here”) and a rule to sort by shape

(e.g. “if rabbit... here” and “if boat...here”). Children ages 3-4 were successful on these sorting tasks when performing them separately, but failed when required to integrate these two within a higher-order rule.

Halford (1993; Andrews & Halford, 2003; Halford et al, 2002) has argued that relational complexity is more generally a constraint on the number of distinct units of information that must be processed in parallel while being maintained in WM in order for a reasoner to complete a task. Using this metric of relational complexity, Halford has argued for a developmental continuum in children’s relational complexity capacity such that until approximately age four, children can process binary relations (a relationship between two objects) but not ternary relations (relationships among three objects, equivalent to the integration of 2 binary relations).

The three hypotheses are not mutually exclusive, and the relationships among the empirical factors emphasized by each model have not been fully examined. The present project examines the interactions among the constraints at the heart of the three models: the role of domain knowledge, inhibition of perceptual distraction, and relational complexity.

Picture Analogy Task

We developed a set of materials for a picture-analogy task suitable for children across a wide age range. The general structure of the stimuli was modeled after those developed by Markman and Gentner (1993), with inclusion of additional controls and using content accessible to young children. Our picture set (Richland Picture Analogies, or RPA task; available from first author upon request) was designed to examine the impact of relational complexity and perceptual distraction (i.e., need for inhibition) on children from age 3 yrs, while controlling for domain knowledge. The RPA stimuli depict relational motion verbs of the type learned early in children’s vocabulary acquisition (e.g., Golinkoff et al., 1996; Golinkoff et al, 1995; Gentner, 1978). Relations were motion verbs with perceptually available meanings that are familiar to young children by the age of 3 (e.g., “kiss”, “chase” and “feed”). The objects used to represent these relations were items regularly encountered by preschool age children, including humans, animals, and dolls. Counterbalanced versions of each picture set factorially varied number of relevant relations (1 or 2) and presence vs. absence of a perceptual distractor in a 2x2 design. Perceptual distractors were either exact matches to the source object located within the target picture or were slight variations of the same object (e.g., a cat chasing and a cat sitting). In the no distractor conditions, a neutral object replaced the featural match. The spatial location was held constant. Unlike in the Markman and Gentner stimuli, distractors were never placed in key relational roles (allowing perceptual and relational errors to be coded separately), and the number of objects in each picture was controlled.

Method

Participants

The participants were 68 children: 22 aged 3-4 years, 21 aged 6-8, and 25 aged 13-14. They were enrolled in preschool, elementary, and junior high school programs in the New York City and Los Angeles areas.

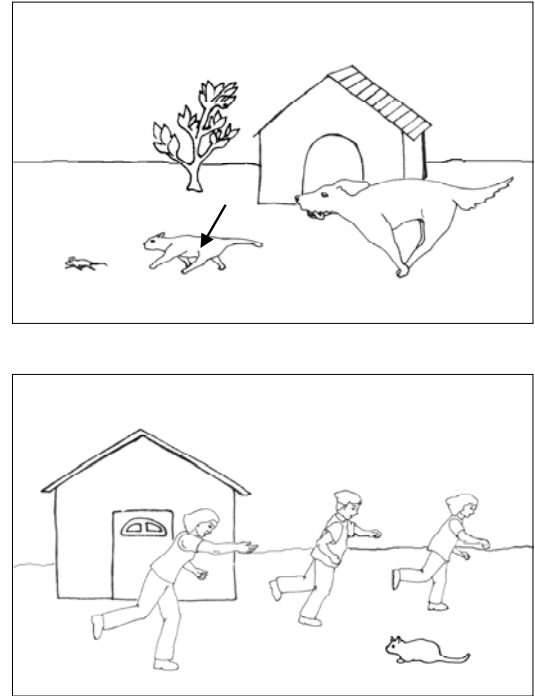
Materials and Design

The RPA task consists of 20 pairs of source and target pictures in which objects in the paired pictures depict the same relationship using unique objects. On a single page, participants viewed the two pictures in a set. An arrow pointed to a source object in the top picture, and the participant was asked to select the corresponding object in the bottom picture (cf. Markman & Gentner, 1993). For the example in Figure 1, the top picture represents “dog chasing cat chasing mouse” and the bottom picture represents “woman chasing boy chasing girl”. If an arrow pointed to the cat, the correct relational response would be the boy in the bottom picture. All pictures contained extra items not depicting the relevant relationship, and the number of total objects was standardized across pictures per condition. Most image sets contain a total of five objects.

Four versions of each picture set were constructed in order to manipulate two variables in a 2x2 design. The first variable was the presence or absence of a perceptual distractor in the target picture, defined by strong featural similarity to an object in the source picture. The featural distractor was either an identical match to an object in the source picture or was the same object in a slightly different position. For example, in Figure 1 (top) the cat is depicted sitting in the target picture but is not involved in the chase. The featural distractor is never involved in the relational structure of the target picture. In Figure 1 (bottom), the correct relational response is the boy; however the participant must inhibit the featural match to make this choice. When present, the featural distractor spatially replaces an alternative object in the target picture. As a control to ensure that the featural distractors were indeed perceptually distracting, ten undergraduates were asked to select the most perceptually similar object to the target in the 2R-D version of each stimuli. Participants selected the intended featural match 96% of the time, indicating that the manipulation of perceptual similarity is valid.

The second variable was the number of relations, one or two, that participants were required to process simultaneously in order to accurately select a target object. When two relations were involved, the correct target object was both agent and recipient of a relation. For example, in Figure 1 the top picture represents “dog chases cat” and “cat chases mouse”, whereas the bottom picture depicts “mom chases boy” and “boy chases girl”. If the participant only considered one of the relations in each picture, there would be two equally plausible answer

choices, and participants would be expected to perform at a 50% level at best. In this example the boy is the correct relational response because he (uniquely) is both being chased and is chasing. Making this determination requires integration of two binary relations in each picture.



Problem 2-2a

Figure 1. Sample stimuli, two relations with distractor (R2-D). The cat in the top picture (both chaser and chased) maps relationally to the boy in the bottom picture.

The 2x2 repeated-measures portion of the design generated four conditions: one relation, no featural distractor (R1-N), one relation with featural distractor (R1-D), two relations, no featural distractor (R2-N), two relations, featural distractor (R2-D). Packets of picture pairs for each participant were organized such that five examples of each condition were included in a random order. The assignment of specific picture pairs to each of the four conditions was counterbalanced across participants in each age group. The three age groups constituted an additional between-subjects factor. The dependent variable was participants' object choice within target pictures.

Procedure

The task was administered to participants in paper form. All participants were given two sample problems,

one involving one relation and the other involving two relations. The instructions stated that “a certain pattern exists in both the top picture and the bottom picture, and the child’s job is to find this pattern.” Following the first sample problem, (a 1R-D problem), it was explained that “some pictures have two parts of the pattern like that one, and others have three parts” (demonstrated subsequently in the 2-relation sample problem). The child was taught that an object in the top picture would be highlighted by an arrow, and they were to point or draw an arrow to the corresponding object in the bottom picture. For both sample problems, children were asked to point to the correct answer and then were given feedback. Feedback was repeated until they gave the correct answer. If they failed initially on both sample problems, their performance on the first 5 problems was used as criteria for exclusion. If participants failed on more than 3 problems, their data was excluded from analysis.

The problems were presented in random order following the sample problems. The task was administered to the 13-14 year old participants in groups; all other children were tested individually by a single experimenter.

Results

Figure 2 presents the proportion of correct relational responses for each of the four picture conditions as a function of age. An analysis of variance (ANOVA) was performed to examine the effects of age, relational complexity, and distractor condition on children’s proportion of correct relational choices. The ANOVA revealed main effects of age, $F(2, 65) = 78.15, p < .001$, featural distraction, $F(1, 65) = 26.07, p < .001$, and relational complexity, $F(1, 65) = 24.83, p < .001$. These results establish that the RPA task is sensitive to age, that the picture manipulations were effective at creating distraction and increasing WM load, and that these constraints actively impede children’s analogical reasoning.

Interactions were examined among age, relational complexity, and distraction. The interaction between age and distractor condition was reliable, $F(2, 65) = 3.15, p = .05$, whereas that between age and relational complexity was not, $F(2, 65) = .57, p = .57$. Importantly, the 3-way interaction was significant, $F(2, 65) = 3.28, p < .05$.

The pattern of interaction was investigated using repeated-measures ANOVAs for each age group separately. Results show that for the youngest children, ages 3-4, there was a main effect of relational complexity, $F(1, 21) = 4.44, p < .05$, a main effect of distractor, $F(1, 21) = 14.08, p < .01$, and a significant interaction between relational complexity and distraction, $F(1, 21) = 4.21, p = .05$. For the 6-7 yr old children there was a main effect of relational complexity, $F(1, 20) = 10.43, p < .01$ and of distraction, $F(1, 20) = 10.31, p < .01$, but no reliable

interaction between these variables, $F(1, 20) = 2.71, p = .116$. Data for the 13-14 yr olds revealed a main effect of relational complexity, $F(1, 24) = 17.66, p < .001$ but not of distraction, $F(1, 24) = 2.21, p = .15$, nor was there a reliable interaction, $F(1, 24) = 1.67, p = .21$.

These data reveal that young children responded correctly well above chance on the one relation, no distractor condition; however, their accuracy fell when either a distractor or an added level of relational complexity (or both) was added. With age this pattern remained similar for 6-7 year olds, but as children reached adolescence, the negative effects of distractor and relational complexity were minimized.

Chance was calculated conservatively as the percent likelihood that a subject would select the correct relational match within the set of reasonable choices. These included relational errors and featural errors, but not extraneous objects. With this criteria, chance differed by condition reflecting the differential number of potential errors ranging from 50% (2 relevant possible answers) for 1R-N to 25% (4 relevant possible answers) for 2R-D. Paired *t*-tests revealed that the youngest children were above chance on all conditions (1R-N: $t(21) = 2.71, p < .05$; 2R-N: $t(21) = 2.43, p < .05$; 2R-D: $t(21) = 2.35, p < .05$) except for the 1R-D condition ($t(21) = 1.10, p = .29$).

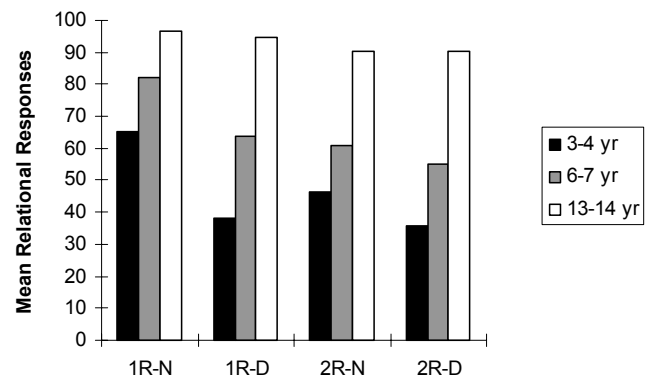


Figure 2. Proportion correct relational responses as a function of distraction and number of relations across age groups.

Error analysis

Children’s responses were categorized into four types (see Table 1). Responses were coded as either (1) relationally correct; (2) relational errors (an object in the correct relation but wrong role); (3) featural errors (the featural match in distractor conditions, or an unrelated object in the corresponding spatial location in no-distractor conditions); or (4) other errors. A repeated-measures ANOVA was performed to examine the relationship between age and participants’ featural errors across the four picture conditions. Children’s choice of

the featural match on the distractor conditions was compared with their choice of a non-featural, matched object in the same spatial location for the no distractor conditions. The main effect of age was reliable, $F(2, 65) = 49.78, p < .001$, as was the main effect of distractor, $F(1, 65) = 126.54, p < .001$, confirming that the featural match was an effective distractor. There was also a significant interaction between age and distractor, $F(2, 65) = 20.15, p < .001$, supporting the hypothesis that perceptual inhibition is a developmental constraint on analogical reasoning. No other interactions were reliable.

Table 1. Proportion of each response type across age and condition.

	Age	R1-N	R1-D	R2-N	R2-D
Correct Relational	3-4	65	38	46	36
	6-7	82	64	61	55
	13-14	97	95	90	90
Featural Errors	3-4	8	46	11	46
	6-7	0	25	4	27
	13-14	0	5	0	8
Relational Errors	3-4	15	9	6	9
	6-7	13	7	19	8
	13-14	2	1	4	4
Other Errors	3-4	9	4	21	6
	6-7	5	5	15	10
	13-14	2	0	4	5

A separate repeated-measures ANOVA was performed on relational errors. Note that there was one possible relational error choice in the R1 conditions, and two such possible error choices in the R2 conditions. The ANOVA revealed main effects of age, $F(2, 65) = 23.41, p < .001$, as well as relational complexity, $F(1, 65) = 59.56, p < .001$. There was also a significant interaction between the presence of a distractor and age on children's relational errors, $F(2, 65) = 5.85, p < .01$. At younger ages children made relational errors more frequently when there was no perceptual distractor available as an option. This finding suggests that young children unsure about the correct answer first attempted to make a feature-based selection; if no perceptually similar choice was available, then they made a guess among objects participating somehow in the relevant relation.

Discussion

Data from the RPA task at ages 3-4, 6-7 and 13-14 provide insight into the roles of relational knowledge, the relational shift, and maturational capacity in children's development of analogical reasoning. Patterns in participants' correct relational responses revealed main effects of age, distraction, and relational complexity, supporting the validity of the task manipulations. These main effects support theories of analogical reasoning

development based on relational complexity and the relational shift.

Conversely, because the 3-4 year olds' performance on the 1R-N condition was high, their subsequent increases in errors in conditions with featural distraction or relational complexity provide support against the theory that domain knowledge alone is the mechanism underlying age-related development of children's analogical reasoning.

Interactions between age, distraction, and relational complexity indicate that in spite of children's capacity to perform analogical mapping based on these relations, as evidenced by their success on the R1-N condition, maturational factors may interact to constrain children's capacity to perform successfully on picture analogies that require more WM or perceptual inhibition.

Further, the error patterns suggest that perceptual distraction may be a primary constraint on children's reasoning and relational complexity a secondary constraint. Error analysis provided support for the claim that participants' patterns of failure were associated with age-related inhibition and relational complexity constraints. Participants were likely to make featural errors when the perceptual distractor was present, highlighting the validity of the distraction manipulation within the task. Supporting the relational shift hypothesis, at 3-4 yrs children were more likely to make featural responses when available than relational errors, even for the 2R-D condition, suggesting that inhibition was a more powerful constraint than relational complexity. However, relational errors were also made by children of all age groups, in highest numbers in the 2R-N condition, indicating that relational complexity is an important constraint on young children's analogical reasoning but may operate secondarily to featural distraction. One possible explanation for this is that inhibition is a core mechanism necessary for the WM system to operate on multiple relations (see Viskontas, in press)

The mechanism underlying featural distraction proposed by Rattermann and Gentner (1998; Gentner & Rattermann, 1991) is domain knowledge; however, this hypothesis is not supported by the current data, as the pictures were simple and counterbalanced across all conditions. The alternative explanation based on an inhibition mechanism is supported by the great difference between children's performance on the R1-N and R1-D conditions, as well as the similarity between the R1-D and R2-D conditions.

In sum, the RPA task provides a new paradigm for using children's interpretations of picture analogies to gather information about children's development of analogical reasoning, and specifically reveals interactions between the roles of perceptual inhibition/ distraction and relational complexity across age.

Acknowledgments

The authors wish to thank the Spencer Foundation (Dissertation Fellowship: Lindsey Richland), the National Institute of Mental Health (MH-64244-01A1; Robert Morrison), Xunesis (www.xunesis.org; Robert Morrison) and the Institute of Education Science (R305H030141; Keith Holyoak) for their generous support. We also thank Ann Fink for drawing the pictures used in the RPA materials. The RPA task is available from the first author upon request.

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