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Analogical reasoning, control and executive functions: A developmental investigation with eye-tracking

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ABSTRACT

We use eye-tracking to study the development of analogical reasoning in 5-year-olds, 8-year-olds, adolescents and adults in the A:B:C:D paradigm. We observed significant differences between groups in the way they explored the space of possible answers to analogy problems. Looking times showed that adults first studied the possible relations between A and B and, thereafter, they moved to C and the solution set. Children, by contrast, tended to start with the C item and organized their search around this item. Children's and adults' saccade patterns differed at the beginning and the end of the trial. Children monitored their search less efficiently than adults (fewer saccades from the solution set to the A–B pair at the end of the trial). Looking patterns associated with errors and correct trials also differed from the start of the trial, suggesting that different search strategies lead to different outcomes. Results are contrasted with current models of analogical reasoning and are discussed in terms of the interaction between the development of executive functions and the control and integration of the information pertaining to the analogy problem.

1. Introduction

Analogy making is typically conceived of as a process in which a *base* domain and a *target* domain are compared in order to find relational correspondences between them (e.g., Gentner, 1983; Holyoak, 2012). For example, in the classical analogies of the A:B:C:D type, one has to identify a relation which might unify the A:B and the C:D pairs, i.e. to find in what terms the stimuli in both pairs play the same semantic role. It has often been argued that analogies play a central role in development because they increase children's knowledge in various conceptual domains (e.g., Brown & Kane, 1988; Goswami, 1992; Gentner, 2010).

Understanding analogies requires systematic comparisons between the items that are activated by the analogy problem. In that sense, analogical reasoning involves a search through a space of solutions. The present manuscript reports the first developmental account of the temporal organization of the search for a solution, obtained through eye tracking data, focusing on the way children and adults integrate the components of the analogy problem. We describe how four age groups (5-, 8-, 13-year olds, and adults) integrate the relations between A–B and between C and the Target or distractors that are semantically related to C.

For most analogy models, the core of analogical reasoning is the mapping process that takes place between the base and the target domains. Mapping involves a set of one-to-one correspondences that link a particular item in the base with an

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item in the target. It also involves candidate inferences, i.e., a search for which relation(s) that hold in the base domain (e.g., A and B) can be applied in the target (e.g., C and D) (e.g., Holyoak, 2012, and the Structure mapping theory, SMT, Gentner 1983).

1.1. Analogies and development

Two general hypotheses have been put forward in order to explain the development of analogical reasoning or, to put it in the above terms, mapping failures or successes. These are the development of the knowledge base and the development of cognitive processes, specifically, executive functions. The development of a *knowledge base* is crucial because knowledge is necessary to find or construct the potential relations for any particular semantic analogy. In order to relate "train and railroad tracks" with "car and road", one must know that trains travel on railroad tracks and that cars travel on roads (Gentner, 1988; Goswami & Brown, 1990). Children are more likely to draw correct analogies in conceptual domains that are the most conceptually accessible to them. For example, Rattermann and Gentner (1998), interpret what Gentner (1988) calls the "relational shift in analogies", i.e., a shift from early attention to featural similarities to later attention to common relational structures, in terms of children's knowledge.

A second line of interpretation, the one adopted in the present contribution, explains the development of analogical reasoning by the progressive improvement of *executive functions* (e.g., Halford, Wilson & Phillips, 1998; Richland, Morrison, & Holyoak, 2006; Thibaut, French, & Vezneva, 2010; Thibaut, French, & Vezneva, 2010; see also Morrison et al., 2004; Viskontas, Morrison, Holyoak, Hummel, & Knowlton, 2004, in aging, for similar views). Executive functions include a set of components such as working memory, flexibility, and inhibition (see Zelazo, Carter, Reznick, & Frye, 1997; Brocki & Bolin, 2004; Senn, Espy & Kaufmann, 2004; for a recent review, Carlson, Zelazo, & Faja, 2013). In this context, inhibition plays a central role in analogy comprehension, especially when salient associations come immediately to mind but are irrelevant to the current analogy. These associations must be inhibited (e.g., in the bird: nest: dog:? (doghouse) case, a strongly associated term to be inhibited would be "bone", see Richland et al., 2006; Thibaut, French et al., 2010; for children and Morrison et al., 2004, in aging people). Cognitive flexibility is required in order to find new relations that make sense in the context of the target analogy, especially when the relations that first come to mind are irrelevant (see Glady, Thibaut, French, & Blaye, 2012).

To illustrate, Richland et al. (2006 Fig. 1, p. 255) used scene analogy problems consisting of pairs of scenes illustrating relations among objects. The authors manipulated a featural distractor in the second scene of each problem. For example, if the base scene included a running cat as part of the relation (i.e., dog *chases* cat), they added a distractor object to the target scene (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 in the *chase* relation in the base scene. Not surprisingly, results revealed that stimuli with similar distractors elicited more errors than the stimuli with dissimilar distractors. The authors also showed that the number of objects or participants involved in a relation (2 or 3) had a significant effect on performance. The executive function view posits that analogy comprehension involves numerous successive comparisons of the available information, especially for difficult analogies, i.e., when the solution is not obvious or/and when many related distractors are present (e.g., Holyoak, 2012; Morrison et al., 2004; Thibaut, French et al., 2010; Bugaiska & Thibaut, 2015).

1.2. The temporal dynamics of analogical reasoning and its development

Analogical reasoning requires integration of multiple sources of information and various comparisons within and between the item pairs making up the problem. The question of the temporal dynamics of the task is an open issue in the literature. In a developmental perspective, we will use eye-tracking to identify significant differences between adults' and children' search patterns, which cannot be done with the standard static performance measures, such as percentage of correct performance. In the eye tracking literature it is well-known that looking times are highly correlated with the independently assessed informativeness of regions within a scene (e.g., Rayner, Shen, Bai & Yan, 2009).

As far as we are aware, apart from a short article by our group, Thibaut, French, Missault, Gérard, and Glady (2011), the present article reports the first developmental study of the dynamics of analogy making with semantic analogies, comparing various age groups. The eye-tracking literature on analogy is restricted to adults (see Salvucci & Anderson, 2001, for verbal-written analogy problems or Gordon & Moser, 2007; who studied looking times and saccades for scenes from Richland et al., 2006).

If analogy making is characterized by comparisons between and within pairs of items, how are these comparisons organized and how do they develop over time? Thibaut, French et al. (2010) characterized analogy making as a search in a semantic space. The space is itself dynamically constructed during the comparisons. In what follows, we contrast predictions of the two general models of development described above.

The knowledge view of the development of analogical reasoning makes no specific claims regarding the temporal organization of the search. In the present experiment, we ensured that the children had the knowledge necessary to solve the analogy. The executive function view makes the general prediction that younger children will have more difficulties solving analogy problems than adults because of their poorer inhibition capacities. However, this says nothing about the time course of the comparison processes that led to the error (or a correct answer). One crucial question is whether children focus more on irrelevant information than adults when solving a problem (Ratterman & Gentner, 1998; Richland et al., 2006; Thibaut,