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Computational models of relational processes in cognitive development

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ABSTRACT

Acquisition of relational knowledge is a core process in cognitive development. Relational knowledge is dynamic and flexible, entails structure-consistent mappings between representations, has properties of compositionality and systematicity, and depends on binding in working memory. We review three types of computational models relevant to relational knowledge. The first are formal models of structural commonalities among concepts, including some that differ in surface characteristics. The second is a self-modifying production system model of the role of relational knowledge in strategy acquisition. The third comprises symbolic connectionist models that implement key properties of relational cognition. These models are complemented by the semantic cognition model that shows how some developmentally important concept acquisition mechanisms can emerge from learning input–output functions. We conclude that no one type of model fully suffices as an account of cognitive development but there is potential for future development, including hybrid models that could meet most or all of the criteria.

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The computational models outlined in this article are designed to implement a theory of development of higher cognitive processes that are characterised as symbolic or analytic and are distinguished by requiring "... access to a single, capacity-limited central working memory resource, ..." (Evans, 2008, p. 270). We propose that relational knowledge provides a conceptual basis for higher cognition (Gentner, 2010; Halford, Wilson, & Phillips, 2010), so our models are designed to implement relational processing. Although our theory is wide ranging, we use transitive inference as our reference task because it is basic to all inference (James, 1890) and there exists a large, high-quality database on it. We distinguish implicit and explicit transitive inference (Goel, 2007); only the latter entails relational representations formed in working memory (Halford, Maybery, & Bain, 1986; Maybery, Bain, & Halford, 1986).

Symbolic processes require a structured operating system to give them meaning (Newell, 1980), just as the natural numbers 1, 2, ... 5, ... 9, ... are given meaning initially by counting and later by other operations such as addition and multiplication. The requirement for structure is consistent with a number of theoretical positions, including gestalt (Wertheimer, 1945), Piagetian developmental (Piaget, 1950), and psychometric (Spearman, 1923). Relations are the essence of structure because, mathematically, a structure is a set of elements on which one or more relations is defined. The theory of relational knowledge has now been applied to analogy (Gentner, 2010; Gick & Holyoak, 1980; Kokinov, Holyoak, & Gentner, 2009), reasoning (see especially mental models theory; Goodwin & Johnson-Laird, 2005; Johnson-Laird, 2005), categorisation (Zielinski, Goodwin, & Halford, 2010) and cognitive complexity (Halford, Wilson, & Phillips, 1998). Relational knowledge processes also play a role in language acquisition (Gentner, 2010; Golinkoff & Hirsh-Pasek, 2008; Naigles, Hoff, & Vear, 2009; Tomasello & Brandt, 2009). For example, the representation of verbs includes an argument structure with inherently relational slots such as *agent*, *patient*, *instrument*.

Relational knowledge has partly replaced logic as a basis for human reasoning. Logic was once considered as constituting the laws of thought (Boole, 1854). Piaget (1950) proposed development through progressively more elaborate psycho-logics as the basis of cognitive development. However, the difficulty of accounting for thought on the basis of logic gave rise to alternatives including information processing models (Anderson, 1991; Andrews & Halford, 2011), heuristics (Kahneman, Slovic, & Tversky, 1982), mental models (Goodwin & Johnson-Laird, 2005; Johnson-Laird, 2005), Bayesian rationality (Oaksford & Chater, 2007), and analogy (Gentner, 2010; Halford, 1993). Relational knowledge has been proposed as an alternative to logic in accounting for cognitive development (Andrews & Halford, 2011; Halford & Andrews, 2004). Relational knowledge can support probabilistic inferences (Halford et al., 2010) and is therefore consistent with Bayesian approaches (Oaksford & Chater, 2007), but the criterion for relational knowledge is representation of relations with the properties outlined later.

Cognitive complexity can be accounted for by the number of entities related in a single representation (Halford, Bain, Maybery, & Andrews, 1998; Halford, Wilson, et al., 1998). The relational complexity (RC) metric has been applied to cognitive development (Halford, 1993), logical inference (Zielinski et al., 2010), mathematics education (English & Halford, 1995), human factors (Boag, Neal, Loft, & Halford, 2006), language (Andrews, Birney, & Halford, 2006), and cognitive neuroscience (Christoff & Owen, 2006; Kroger et al., 2002). The RC metric has also made it possible to predict previously unrecognised cognitive capacities, as in the balance scale (Halford, Andrews, Dalton, Boag, & Zielinski, 2002). Halford, Cowan, and Andrews (2007) present a method for analysis of relational complexity that provides details of assessment criteria.

A correspondence across tasks of equal structural complexity exists, even when they belong to different domains. Andrews and Halford (2002) assessed transitivity, hierarchical classification, class inclusion, cardinality and sentence comprehension in children aged 3–8 years. In each case, tasks of higher relational complexity were more difficult and attained at a later age than closely matched tasks of lower relational complexity. Relational complexity accounted for 80% of age-related variance in fluid intelligence. Tasks of equal relational complexity constituted an equivalence class that transcended task variables and content domains. The structural similarity of transitivity and class inclusion tasks is portrayed in Fig. 1. Thus, relational complexity defines a deep structural property of cognitive processes. By contrast, Piagetian tasks have generally been found not to be equivalent across

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