PAPER

A computational account of children's analogical reasoning: balancing inhibitory control in working memory and relational representation

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Abstract

Theories accounting for the development of analogical reasoning tend to emphasize either the centrality of relational knowledge accretion or changes in information processing capability. Simulations in LISA (Hummel & Holyoak, 1997, 2003), a neurally inspired computer model of analogical reasoning, allow us to explore how these factors may collaboratively contribute to the development of analogy in young children. Simulations explain systematic variations in United States and Hong Kong children's performance on analogies between familiar scenes (Richland, Morrison & Holyoak, 2006; Richland, Chang, Morrison & Au, 2010). Specifically, changes in inhibition levels in the model's working-memory system explain the developmental progression in US children's ability to handle increases in relational complexity and distraction from object similarity during analogical reasoning. In contrast, changes in how relations are represented in the model best capture cross-cultural differences in performance between children of the same ages (3–4 years) in the United States and Hong Kong. We use these results and simulations to argue that the development of analogical reasoning in children may best be conceptualized as an equilibrium between knowledge accretion and the maturation of information processing capability.

Introduction

Analogy provides a framework for comparing the structure of elements within a domain with the structure of elements of other elements in the same or another domain (Gentner, 1983; Gick & Holyoak, 1980). In other words, the elements of a source may be compared and subsequently mapped to a target. An important consequence of this comparison process is the ability to make inferences about the elements of the target domain. Thus analogy is an important way that people can learn about new things based on prior knowledge (Holyoak & Thagard, 1995; Hofstadter, 2001). Children's development of analogical reasoning allows them to notice correspondences and make inferences about relationally similar phenomena across contexts. This skill greatly enhances their capacity for transfer of learning and schema abstraction, two essential aspects of children's learning and cognitive development (Chen, Sanchez & Campbell, 1997; Gentner, 1977; Goswami, 2001; Halford, 1993; Holyoak, Junn & Billman, 1984). While many have argued that analogy is important for children's cognitive development, there is considerable disagreement on the mechanisms underlying children's development of mature, adult-like analogical reasoning.

Computational models of analogy have contributed immensely to understanding the constraints shaping analogical reasoning in adults (e.g. Falkenhainer, Forbus & Gentner, 1989; Holyoak & Thagard, 1989a, 1989b; Hummel & Holyoak, 1997, 2003; Keane & Brayshaw, 1988; Keane, Ledgeway & Duff, 1994; Morrison, Krawczyk, Holyoak, Hummel, Chow, Miller & Knowlton, 2004; Viskontas, Morrison, Holyoak, Hummel & Knowlton, 2004); however, they have played a relatively minor role in helping to elucidate the factors important for the development of analogical reasoning in children (see Doumas, Hummel & Sandhofer, 2008; Halford, Wilson, Guo, Gayler, Wiles & Stewart, 1994; Gentner, Rattermann, Markman & Kotovsky, 1995; and Leech, Mareschal & Cooper, 2008, for notable exceptions). Our intent in this paper is to demonstrate the efficacy of using a neurally inspired symbolic-connectionist computational model of analogy (i.e. LISA; Hummel & Holyoak, 1997, 2003) to examine how various factors important for analogical processing relatively impact the development of analogical reasoning in children.

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Developmental change in analogy

Hypotheses for explaining age-related behavioral differences have typically focused on the importance of relational knowledge acquisition or on the maturation of executive resources including working memory and/or inhibitory control.

Relational knowledge

Relational primacy

Goswami (1992, 2001; Goswami & Brown, 1989) has argued that children are attuned to and able to map relations in a rudimentary manner from early infancy, but their later analogical reasoning skills build on prerequisite content knowledge. Citing Piaget's tasks using fairly sophisticated relations such as 'steering mechanism', as an example, Goswami argues that children must have the necessary relational knowledge in order to reason analogically; however, given that knowledge they should be successful in reasoning analogically. Knowledge is thus viewed somewhat quantitatively, such that with greater knowledge acquisition one accrues increasing numbers of prerequisites to reason analogically across more and varied contexts.

Relational shift

In an alternative theoretical framework, Gentner and Rattermann (1991; Gentner, 1988; Rattermann & Gentner, 1998) have posited a causal role for knowledge acquisition in shifting children's reasoning from focusing on object properties to focusing on relations. They hypothesized a domain-specific 'relational shift' during cognitive development such that as children build knowledge in a domain, they move from attending to similarity based on object features (i.e. perceptual properties of the entities being compared) to relational similarity (i.e. correspondences between the relations in each entity being compared). This hypothesis is supported by patterns identified in children's processing of metaphors (Billow, 1975; Gentner, 1988) and causal analogies (Rattermann & Gentner, 1998), as well as children's ease of making analogies in very familiar domains (e.g. the human body; Inagaki & Hatano, 1987).

Proponents of the relational shift hypothesis postulate that change in a child's analogical reasoning is not age-related *per se*, but rather is directly tied to knowledge acquisition. The relational shift is domain specific, based upon knowledge acquisition, and can be observed in adults when learning new content as well as children (Gentner & Ratterman, 1991). This argument aligns with classic findings demonstrating that adult experts in a domain tend to attend to relations, while novices attend to object features (Chi, Feltovich & Glaser, 1981).

Gentner *et al*. (1995) used the structure mapping engine (SME) to model the results of Gentner and Ratterman (1991), and modeled the relational shift by using more 'object-centered' representations, containing only lower-level relational representations, to model younger children, and using more 'relation-centered' representations, using a higher-order relation to link two lower-level relations, to model older children and adults. Because of the systematicity constraint, SME showed a mapping advantage for the representation containing the higher-order relation. It is interesting to note, however, that while this solution does result in improved performance in SME, it also results in an increase in processing demands for the system. This is not a problem for SME because the model is not subject to processing constraints, but may suggest that the solution is not plausible for humans with limited working-memory capacity. It is also important to note that technically both representations are relation centered (not object centered) in that they both make explicit use of relations. While this rerepresentation of knowledge can account for the change in reasoning noted by Gentner and Ratterman in SME, it does not explain why children sometimes do not reason relationally in spite of being fully aware of the relations in use (Goswami, 1991) and demonstrating knowledge of higher-order relations (Richland *et al*., 2006).

More recent work suggests that the relational shift may have more to do with pragmatics rather than just a shift. Specifically, reasoners may develop skills to determine whether object or relational similarity provides the information necessary to solve a particular problem (Bulloch & Opfer, 2009). In a task with 3-, 4-, 5-year-olds and adults, older children and adults were more sensitive to the predictive accuracy of each type of similarity. On problems where relational similarity was predictive, these participants made more relational judgments over time, while on problems in which object similarity was more predictive, participants made increasing object similarity judgments.

In an alternative to Gentner *et al*.'s (1995) approach, Leech *et al*. (2008) have proposed a theory of relational priming as a mechanism for the development of children's ability to make analogies. Citing the lack of an explicit theory of how structured representations are learned, this approach posits that analogy does not use explicit representations of relations. Instead, relations are state transformations, and analogy is simply priming of one state given another as a cue. The challenge with this model of knowledge acquisition is to explain the difficulty of documenting implicit relational priming in adults (Spellman, Holyoak & Morrison, 2001), and children's and adults' ability to reason about relations in explicit, flexible ways that are unsupported by implicit representations (e.g. Brown & Kane, 1988; Kotovsky & Gentner, 1996; Namy & Gentner, 2002; Smith, 1984; Holyoak & Thagard, 1995). In addition, Doumas *et al*. (2008) have recently proposed a theory and implemented a computational model (DORA) of how explicit structured representations can be learned from unstructured examples, thereby eliminating one of the major

criticisms of using structured representations to simulate analogical reasoning.

Knowledge rerepresentation

An information processing view provides a third perspective on the role of knowledge acquisition in children's development of analogical reasoning. Based on this perspective, we posit that while a prerequisite knowledge base is essential, qualitative changes in relational knowledge representations can reduce processing demands. Doing so would thereby free resources to enable more sophisticated analogical reasoning within the constraints of limited working-memory capacity at any given point during maturation. This is of particular importance for young children, since resources known to be required for analogical reasoning such as working-memory capacity and inhibitory control (Baddeley, Emslie, Kolodny & Duncan, 1998; Krawczyk, Morrison, Viskontas, Holyoak, Chow, Mendez, Miller & Knowlton, 2008; Kubose, Holyoak & Hummel, 2002; Morrison, Holyoak & Truong, 2001; Morrison *et al.*, 2004; Morrison, 2005; Viskontas *et al.*, 2004; Waltz, Knowlton, Holyoak, Boone, Mishkin, de Menezes Santos, Thomas & Miller, 1999; Waltz, Lau, Grewal & Holyoak, 2000) gradually increase during childhood (e.g. Bjorklund & Harnishfeger, 1990; Diamond, 2002; Diamond, Kirkham & Amso, 2002).

Executive resources

Knowledge acquisition alone does not appear to explain all identified patterns of analogical reasoning (Goswami, 1991). Even when knowledge is held fairly constant across conditions, children exhibit differential success on analogical reasoning problems depending on the executive resources demanded of the problems themselves (Richland *et al.*, 2006).

Relational complexity

Halford (1993) has argued for a primary role of maturation of children's working-memory capacity in development of children's analogical reasoning. In particular, he has argued that working-memory capacity is crucial to the ability to process complex relations, an important characteristic of mature, adult analogical reasoning. Halford and colleagues (Andrews & Halford, 2002; Halford, Andrews, Dalton, Boag & Zielinski, 2002) have demonstrated that young children have difficulty in complex relational tasks in which they must process multiple relations simultaneously. Specifically, they proposed a theory of *relational complexity* to categorize relations by the number of sources of variation that are related and must be processed in parallel. For example, the simplest level of relational complexity, a binary relation, is defined as a relationship between two arguments, both of which are sources of variation. Thus 'boy chases girl' specifies a single relation (*chase*) between two arguments (boy and girl). A reasoner would have to hold both arguments and the relevant relation in mind to reason on the basis of this relationship. The next level of relational complexity, a ternary relation, includes three arguments as sources of variation. Integrating two binary relations with three arguments such as 'Mom chases a boy who chases a girl' is also considered a ternary relation. Halford (1993) suggested that on average, children's working-memory capacity is such that after age 2, children can process binary relations (a relationship between two objects), and after age 5 they could process ternary relations. Thus, children of age 2 could perform very simple analogy problems, but not problems that require integrating multiple relations.

Inhibitory control

Zelazo, Frye and colleagues (1998; Zelazo, Müller, Frye & Marcovitch, 2003) have identified similar age-related progressions using an alternative formulation of relational complexity that focuses more directly on the importance of inhibition in executive control. According to their Cognitive Complexity and Control (CCC) theory, the number of conflicting hierarchical rules that must be maintained in order to accomplish a task defines complexity. For example, in the Dimensional Change Card Sort task, children were given one set of sorting rules (color or shape) and then asked to sort by a new rule. Children ages 3–4 were successful on each sorting task when performing them separately, but failed when required to integrate these two to determine which rule to use. They explain this failure as a maturational limitation in reflective consciousness and executive function.

While the relational complexity theory has been proposed in opposition to knowledge acquisition theories of analogical reasoning development, other findings suggest that executive resources and at least the relational shift may be closely related. Markman and Gentner (1993) developed an analogy mapping task for use with adults, which allowed participants to reason based on either relational or object similarity. Using this task, Waltz *et al.* (2000) found that increases in working-memory load shifted adult participants from using relational similarity to using object similarity to complete the task. It is not clear, however, how working-memory load affects this balance. One possible explanation is that working-memory load utilizes the inhibitory resources in working memory necessary to suppress responses based on the salient features of objects during relational processing and object matching, an argument previously made by Morrison and colleagues (2004) to help explain analogical reasoning performance in frontal patients (see also Krawczyk *et al.*, 2008) and older adults (Viskontas *et al.*, 2004).

Likewise, Richland *et al.* (2006) proposed that inhibitory control might help to explain the relationship

between maturation and the impact of object similarity in young children. While inhibitory control has been a major topic in models of cognitive development (e.g. Bjorklund & Harnishfeger, 1990; Diamond, 2002), it has not previously been applied to understanding the development of analogy. However, the hypothesis that inhibitory control is important for the development of analogy is consistent with results from other cognitive tasks (e.g. Diamond *et al*., 2002; Lorsbach & Reimer, 1997; Zelazo *et al*., 2003). In one example, Diamond *et al*. (2002) manipulated the day-night task, a Stroop-type task in which children are instructed to say 'day' when shown a picture of a moon and 'night' when shown a picture of a sun. Inhibitory control is tested because presumably children's semantic category of 'day' becomes activated when they are shown a scene depicting a sun, but they are instructed instead to generate a word with the opposing semantic meaning, 'night'. Children under the age of 4½ consistently failed on the task. When Diamond and colleagues reduced the inhibitory requirements of the task by asking participants to say 'dog' and 'pig' instead of 'day' and 'night', young children performed much better, suggesting that limits in their inhibitory control explained low success rates in the day-night version of the task.

Changes in inhibitory control have already been useful in explaining analogy performance in several other groups associated with compromised executive functions. For example, Morrison *et al*. (2004) found that patients with damage to the prefrontal cortex showed a preference for using featural over relational similarity in an analogy mapping task, much like college students under dual-task conditions (Waltz *et al*., 2000). In a follow-up study, they systematically manipulated the need for suppression in a verbal analogy task and found this was the best predictor of the change in performance in analogy problems of low relational complexity. Similar results with frontal patients were also found in a forced-choice visual analogy task which required patients to choose between a relational match and either a semantic, perceptual, or unrelated distractor, with patients frequently choosing semantic distractors over relational matches (Krawczyk *et al*., 2008). Likewise, Viskontas and colleagues (2004) showed that changes in inhibitory control in working memory could account for older adults' deficiencies in processing visual analogies that required relational integration and inhibition. We believe similar changes may also help to explain changes in featural and relational responding as documented by Rattermann and Gentner (1998; Gentner & Rattermann, 1991).

In our present effort we focus on understanding how changes in inhibitory control in working memory may be able to explain changes in children's analogy performance characterized by both relational complexity and featural distraction, and how representation of relational knowledge can help to reduce the demand for this resource, and thus help to explain a cultural difference in analogy performance.

A computational account of analogy

In an effort to understand the factors behind changes in children's analogical reasoning in scene analogy problems, we modeled results from Richland *et al*. (2006) and Richland *et al*. (2010) in LISA (Learning and Inference with Schemas and Analogies; Hummel & Holyoak, 1997, 2003). The four counterbalanced versions of an example problem from these two experimental papers are provided in Figure 1.

Learning and Inference with Schemas and Analogies (LISA) architecture

LISA is a neurally inspired computational model of relational reasoning. LISA uses temporal synchrony to dynamically bind distributed (i.e. connectionist) representations of relational roles to distributed representations of their fillers in working memory. Importantly, because LISA dynamically binds representations of relational roles to their arguments (i.e. because it solves the binding problem; see Hummel, Holyoak, Green, Doumas, Devnich, Kittur & Kalar, 2004), LISA's representations support structured (i.e. explicitly relational) processing. While the explicit structured representations utilized by LISA can be 'hand-coded' by the researcher, they can also be generated from unstructured examples by using an extension of LISA called DORA (Doumas *et al*., 2008).

When LISA 'thinks about' a proposition, it fires roles *in* synchrony with their fillers, and fires separate role-filler bindings *out of* synchrony with one another. The synchronized (and de-synchronized) patterns of activation serve as the basis for memory retrieval, analogical mapping and inference, and schema induction (see Hummel & Holyoak, 1997, 2003). LISA has previously been used to account for changes in reasoning with age (Viskontas *et al*., 2004) and with damage to either the prefrontal or anterior temporal cortex (Morrison *et al*., 2004).

LISA represents relational structure using a hierarchy of distributed and localist codes (see Figure 2 for a schematic representation of LISA's architecture as applied to the proposition *chase* (cat, mouse)). At the bottom of the hierarchy, *semantic* units (small circles in Figure 2) represent objects and relational roles (i.e. predicates) in a distributed fashion. For instance, each role of the *chase* relation would be represented by semantic units such as *aggressor* for the first *chase* role (*chaser* or c1 in Figure 2), *victim* for the second role (*chased* or c2 in Figure 2), and *pursuit* for both. Similarly, the arguments 'cat' and 'mouse' would be represented by units specifying their meaning (e.g. cat: cat, pet; mouse: mouse, pest; both: animal). The exact content of the semantic units is not important to LISA's operation; they might be whatever is meaningful to describe the predicates and objects and more importantly whatever is neurally plausible to do so. At the next
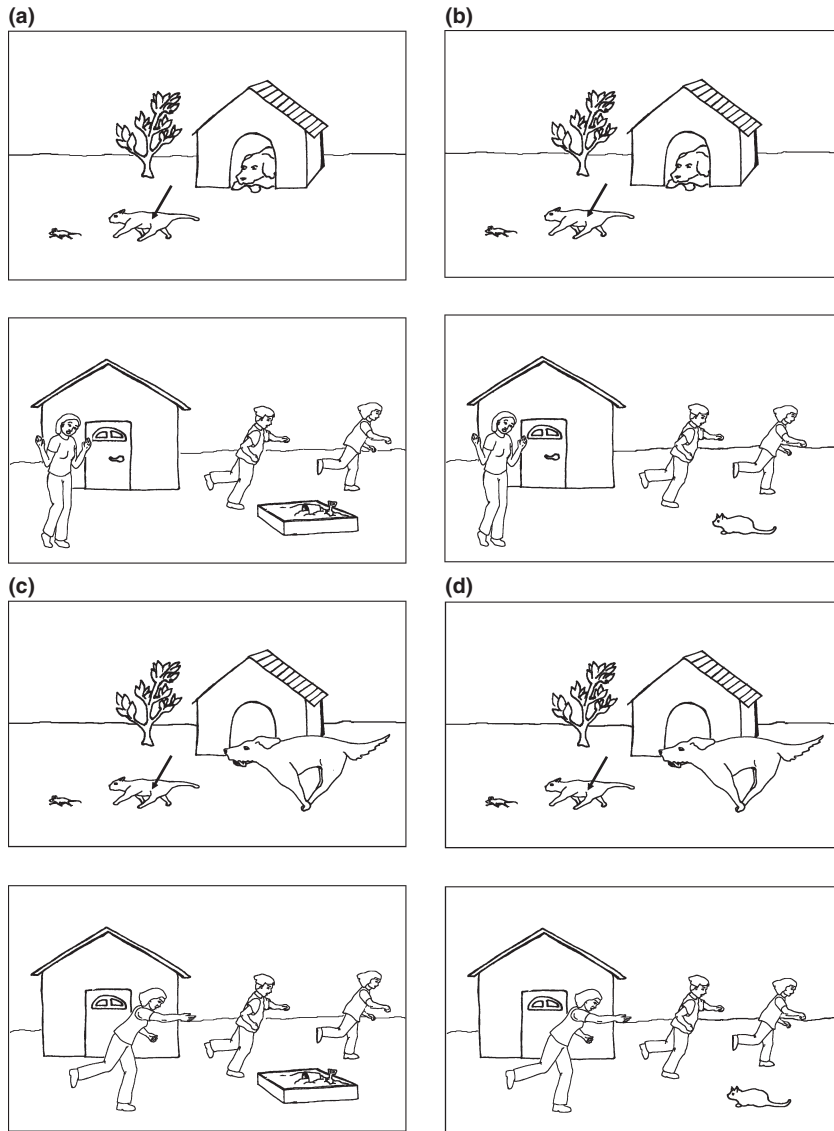
Figure 1 *Counterbalanced versions of the 'chase' Scene Analogy Problems (Richland, Morrison & Holyoak, 2006): (a) 1-Relation/ No Distractor, (b) 1-Relation/Distractor, (c) 2-Relation/No Distractor, (d) 2-Relation/Distractor.*

level of LISA's hierarchy, localist *predicate* and *object* units (triangles and large circles, respectively, in Figure 2) represent relational roles and their arguments and have bi-directional excitatory connections to the corresponding distributed semantic units. Sub-proposition (SP) units (rectangles in Figure 2) bind roles to their arguments, and have bi-directional connections to the corresponding predicate and object units. In the case of *chase* (cat, mouse), one SP would bind 'cat' to the first role of *chase* (i.e. *chaser*, $c1$), and another would bind 'mouse' to the second role (i.e. *chased*, $c2$). At the top of the hierarchy, proposition units link role-filler bindings (i.e. SPs) into complete propositions via excitatory connections to the corresponding SPs. In addition to the excitatory connections already mentioned, localist units also have bi-directional inhibitory connections between units of the same type. For instance, cat and mouse would have an inhibitory connection, as would

the two SP units representing the chaser/cat and chased/mouse role bindings.

A complete analog (i.e. situation, story or event) is represented by the collection of semantic, predicate, object, SP and proposition units that collectively code the propositions in that analog. For instance, Figure 3 shows a representation for a 1-Relation with Distractor scene analogy problem shown in Figure 1b. This representation includes both an analog in the driver and two competitive recipient analogs. Analogs in the driver and recipient do not share object, predicate, SP or proposition units; however, all analogs in LISA's long-term memory are connected to the same set of semantic units. Thus, the distributed semantic units permit the localist (i.e. proposition, SP, predicate, and object) units in one analog to communicate with the units in other analogs.

For the purposes of memory retrieval and analogical mapping (Hummel & Holyoak, 1997) as well as
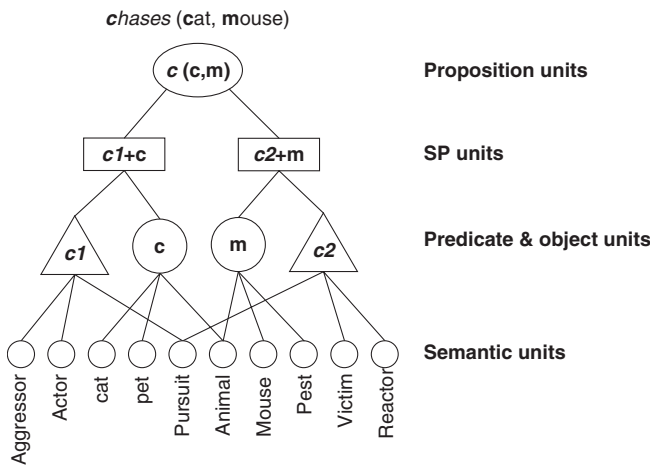
Figure 2 *LISA architecture for proposition chases (cat, mouse) showing the hierarchical arrangement of localist (i.e. proposition, SP, predicate, object) and distributed (i.e. semantic) units.*

analogical inference and schema induction (Hummel & Holyoak, 2003), analogs are divided into two mutually exclusive sets: a *driver* and one or more *recipients*. The driver controls the sequence of events: propositions in the driver become active (i.e. enter working memory) one at a time. When a proposition enters working memory, the binding of its roles to their arguments is represented by synchrony of firing: All the units under a given SP fire in synchrony with one another, and separate SPs fire *out of* synchrony with one another. The result on the semantic units is a set of mutually desynchronized patterns of activation (see Figure 4bi): one pattern for each active SP (i.e. role binding) in the driver. In the case of *chase* (cat, mouse), the semantic units of 'cat' (e.g. cat, pet, animal) would fire in synchrony with the features of the first role of *chase* (i.e. *chaser*, c1), while the semantic units representing 'mouse' (e.g. mouse, pest, animal) fires in synchrony with the second role (i.e. *chased*, c2). This oscillatory pattern of systematic SP activation and

deactivation results from the inhibitory connections between SPs and is intrinsic to LISA's operation.

In order to represent the proposition *chase* (mouse, cat), LISA activates exactly the same semantic units, but their synchrony relations are reversed ('mouse' fires in synchrony with the *chaser* (i.e. c1), and 'cat' fires with *chased* (i.e. c2)). The resulting patterns of activation on the semantic units drive the activation of the localist units representing the relational structure in the various recipient analogs, and serve as the basis for analogical mapping, inference, schema induction, and the other functions LISA performs (Hummel & Holyoak, 1997, 2003). Each set of SPs from a given analog is referred to as a working-memory phase set. For LISA to completely 'think about' an analog, all of the SPs making up the propositions for that analog must time-share in the working-memory phase set.

The final component of the LISA architecture is a set of *mapping connections* between units of the same type (e.g. object to object, predicate to predicate, etc.) in the driver and the various recipient analogs (see Figure 5). These connections grow (via Hebbian learning) whenever corresponding units in the driver and recipient fire at the same time. They permit LISA to learn the correspondences (i.e. mappings) between analogous units in separate analogs. They also permit correspondences learned early in mapping to influence the correspondences learned later.

Inhibition in working memory in LISA

In addition to providing an account of human relational reasoning, LISA also serves as a model of working memory. When a proposition is fired, one of its role bindings (SPs) enters the focus of attention in working memory. Likewise, all of the units connected either directly or indirectly in long-term memory receive activation. The various SPs timeshare the limited-capacity
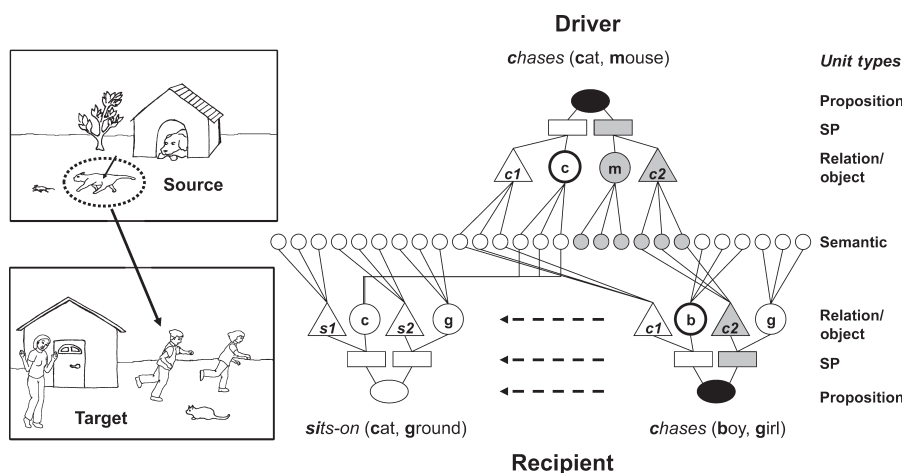

Figure 3 *LISA rapidly learns what in the recipient goes with what in the driver by using a Hebbian learning algorithm to track what units of the same type are firing at the same time. These 'mapping connections' are the basis for analogical mapping and inference. Here the mapping connections from various object units in several recipient analogs are shown to the cat object unit in the driver.*
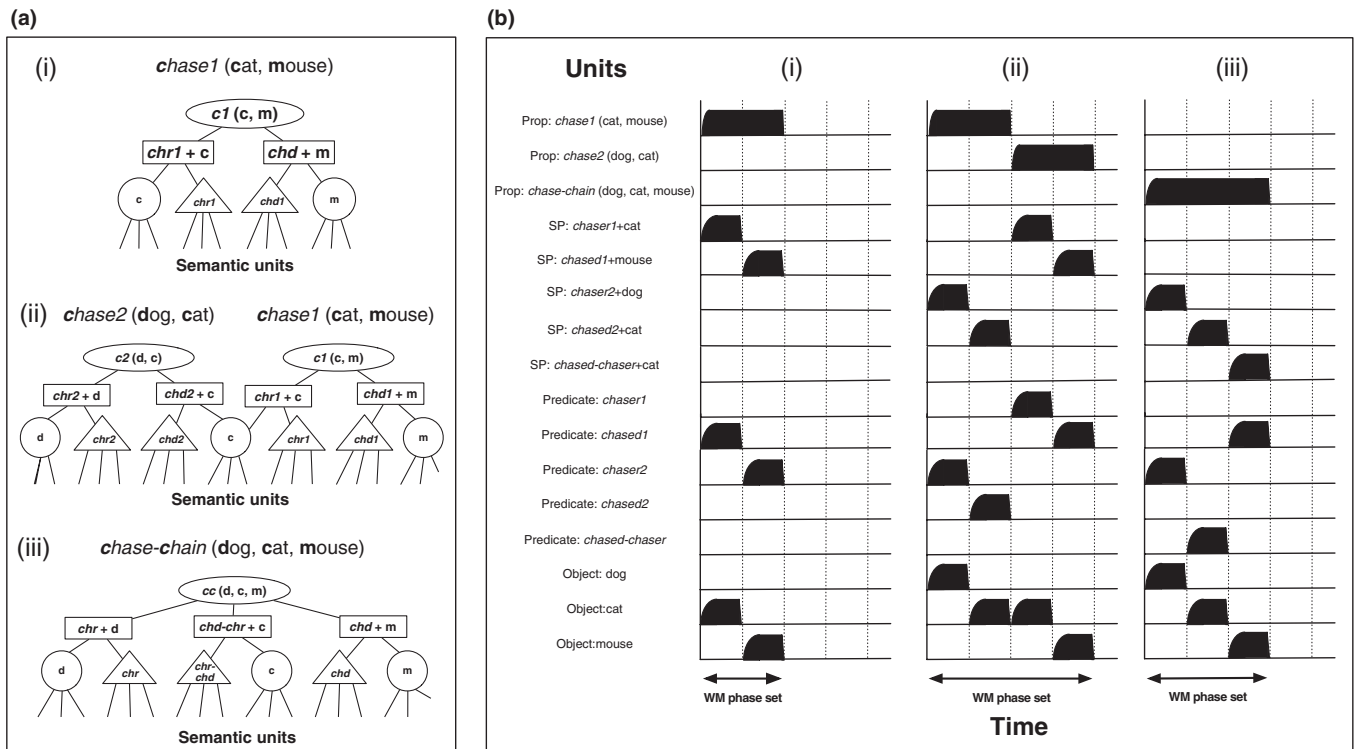
Figure 4 *(a) LISA representations for the driver of scene analogy problems showing (i) a 1-Relation problem, (ii) a 2-Relation problem represented with two propositions, and (iii) a 2-Relation problem where the relations have been chunked into a single three-place proposition. (b) Firing diagrams for the three representations showing the various 'phases' of firing to fully capture the relational structure in each type of problem. Note that chunking the 2-Relation problem (iii) results in a smaller (i.e. shorter) WM phase set relative to the unchunked 2-Relation problem (ii) and that both 2-Relation representations have a larger WM phase set than the 1-Relation problem (i).*

focus of attention; however, recently activated units remain in active memory – their activation decaying over time if they are not brought back into the focus of attention. This conception of working memory is similar to that developed by Cowan (1995), Fuster (2008) and Kane and Engle (2002), where working memory involves neurons in prefrontal cortex activating neurons in posterior cortex representing information in long-term memory. As detailed below, the systematic activation and dynamic binding of information stored in long-term memory in LISA's working memory is critically dependent on inhibition, a cognitive function frequently associated with the prefrontal cortex (e.g. Morrison *et al.*, 2004; Perret, 1974; Shimamura, 2000) and frequently cited as important in human development (e.g. Bjorklund & Harnishferger, 1990; Diamond, 2002, Hasher & Zacks, 1988, Viskontas *et al.*, 2004).

Of particular importance to the present simulations, inhibition plays a role in the selection of items to enter working memory because selection is a competitive process: Propositions in the driver compete to enter working memory on the basis of several factors, including their pragmatic centrality, or importance, support from other propositions that have recently fired, and the recency with which they themselves have fired. Reduced driver inhibition results in reduced competition and more random selection of SPs to fire. The selection of which

SPs are chosen to fire, and in what order, can have substantial effects on LISA's ability to find a structurally consistent mapping between analogs. It follows that reduced driver inhibition, resulting in more random selection of propositions into working memory, can likewise affect LISA's ability to discover a structurally consistent mapping.

The role of inhibition in the activity of a recipient analog is directly analogous to its role in the activity in the driver. Recipient inhibition causes units in the recipient to compete to respond to the semantic patterns generated by activity in the driver. If LISA's capacity to inhibit units in the recipient is compromised, then the result is a loss of competition, with many units in the recipient responding to any given pattern generated by the driver. The resulting chaos hampers (in the limit, completely destroys) LISA's ability to discover which units in the recipient map to which in the driver. In short, inhibition determines LISA's working memory capacity (see Hummel & Holyoak, 2003, Appendix A; Hummel & Holyoak, 2005), controls its ability to select items for placement into working memory, and also regulates its ability to control the spread of activation in the various recipient analogs. As such, inhibition in LISA is critical for the model's ability to favor relational similarity over featural similarity. This conception is also highly complementary to that presented by Zelazo and colleagues
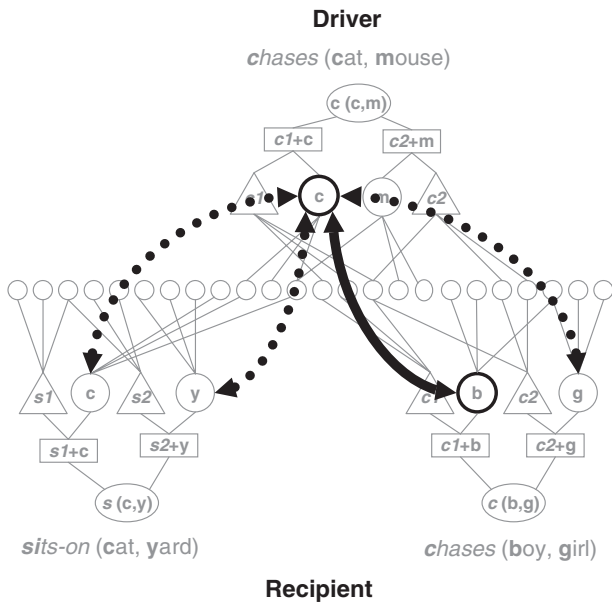
Driver

*ch*ases (**c**at, **m**ouse)

*s*its-on (**c**at, **y**ard)   *ch*ases (**b**oy, **g**irl)

Recipient

Figure 5 *Mapping connections in LISA. Temporal synchrony results in the growth of mapping connections (via Hebbian learning) in LISA between like types of units in the driver and recipient. These mapping connections are the basis of analogical mappings, which in this case allow LISA to 'decide' that the boy in the recipient goes with the cat in the driver.*

(1998, 2003) who describe the need to inhibit one rule (relational structure) in the service of another.

LISA simulations

To test whether LISA's architecture could explain the major trends identified in children's developmental pathways of analogical reasoning, we used LISA to simulate children's performance on scene analogy problems (Richland *et al.*, 2006). These problems had been created to examine the relative effects of distraction from object-based features (relational shift) and relational complexity when prerequisite knowledge was likely and effectively held constant across conditions. These problems were tested with English and Chinese (Cantonese) speaking children to reflect the variety of developmental trends across cultures.

Scene analogy problems

Richland *et al.* (2006) developed a set of scene analogy problems to investigate relational complexity and featural distraction within a single analogical reasoning task based on a paradigm originated by Markman and Gentner (1993). The relations and the objects used to represent them were familiar to preschool age children (see Richland *et al.*, 2006, Experiment 2).

Figure 1 depicts an example of each of the four counterbalanced versions that were created for each of

the 20 picture sets. Each set of problems factorially varied (1) the number of instances of the relevant relation that needed to be mapped (1-Relation or 2-Relation), and (2) the presence of an object in the target scene that was either featurally similar (Distractor) or dissimilar (No-Distractor) to the object to be mapped in the source scene. 2-Relation problems were created by having one object that was not involved in the principal relation (dog in Figure 1a and 1b) in the 1-Relation problems participate in the principal relation for the 2-Relation version (*chase* (dog, cat)). Distractor and No-Distractor versions were created by having an extra object in the same picture that was either similar (sitting cat in Figure 1b and 1d) or dissimilar (sandbox in Figure 1a and 1c) to the item to be mapped in the source picture (running cat). Children were asked to indicate which object in the target picture corresponded to the indicated object in the source picture (the running boy in the example in Figure 1).

United States children

In a series of experiments with children from the United States (US), Richland *et al.* (2006) found reliable effects of both relational complexity and featural distraction on children's analogical reasoning ability (see Figure 6). Specifically, 3–4-year-olds showed strong effects of both distraction and relational complexity that interacted to reveal the highest accuracy in the 1-Relation/No-Distractor condition and the lowest accuracy in the 2-Relation/Distractor condition. This pattern was similar for the 6–7-year-olds, with main effects of both relational complexity and distraction. In contrast, the 13–14-year-olds showed a main effect of relational
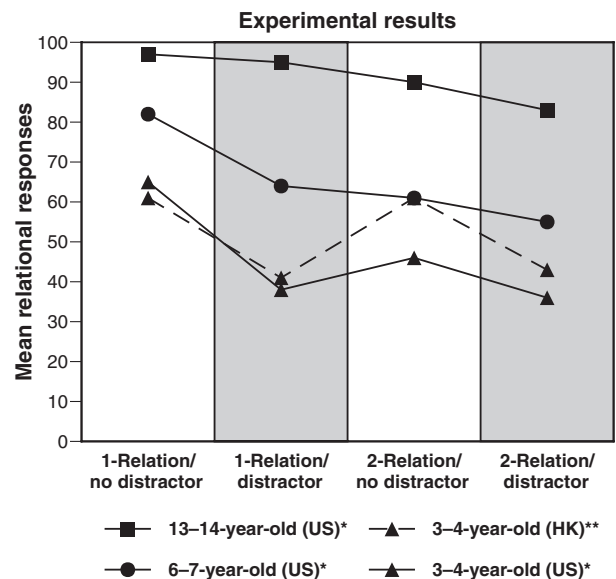

Figure 6 *Experimental results from several experiments (Richland* et al., *2006, Experiment 1; Richland* et al., *2010) using the scene analogy problems with children.*

complexity but no effect of distraction. In a second experiment, Richland *et al.* (2006) demonstrated that these effects in young children were not due to problems in identifying the relevant relations.

Error data confirmed that these patterns in accuracy showed corresponding developmental effects of both relational complexity and object similarity distraction. Increasing the level of relational complexity raised the number of relational errors in the youngest children the most, with decreasing numbers with age. Adding a featural distractor led to greater object similarity errors in the youngest children in contrast to the oldest children who showed no effect. Interestingly, when children solved problems with both a featural distractor and two levels of relational complexity, featural errors, as opposed to relational complexity errors, were the most common.

Children from Hong Kong

As a follow-up to our study with US children, we investigated whether 3–4-year-old native Cantonese speakers from Hong Kong (HK) showed the same pattern as US children (Richland *et al.*, 2010). Based on their different relational knowledge base as well as their different experience with reasoning about relations, we believed Chinese children would perform differently than the US children on the scene analogy problems. Adult studies have shown cultural differences in normative patterns for drawing relational inferences (see D'Andrade, 1995; Hansen, 1983; Ji, Peng & Nisbett, 2000; Nisbett, 2003) such that Chinese and Japanese reasoners may be more attuned to relational correspondences than US participants. These differences also appear in cross-cultural variations in children's socialization and linguistic routines, with Asian caregivers using more action-oriented language and referential verbs in play and caregiving than relatively object-focused US caregivers (e.g. Korean: Au, Dapretto & Song, 1994; Gopnik, Choi & Baumberger, 1996; Japanese: Fernald & Morikawa, 1993; Ogura, Dale, Yamashita & Murase, 2006; Chinese: (Mandarin) Tardif, 1996; Tardif, Gelman & Xu, 1999; Tardif, Shatz & Naigles, 1997; (Cantonese) Leung, 1998). Chinese children themselves may additionally show a higher relative rate of verb usage in Mandarin (Tardif, 1996; 2006; Tardif *et al.*, 1997; Tardif *et al.*, 1999) and Cantonese (Tse, Chen & Li, 2005) than US children of comparable ages who show a more pronounced noun bias (see Gentner, 1981, 1982; Gentner & Boroditsky, 2001).

These children's greater experience with relational language and socialization suggests that they may have a greater expertise in representing relational information. Thus, we hypothesized that children from Hong Kong (HK) may tend to construct a somewhat different, and potentially more expert, representation of 2-relation problems than US children. There was no theoretical reason to expect differences in processing capacity (Hedden, Park, Nisbett, Ji, Jing & Jiao, 2000) or baseline

knowledge of the task since it was a novel task for everyone with simple relations (for more information see Richland *et al.*, 2010).

Data were collected with 61 3- and 4-year-old children who were native Cantonese speakers. Participants were sampled from Chinese preschools with similar demographics to the previously tested US population. Like the US children, children from HK showed a similar effect of distraction, favoring the featurally similar distractor to the relationally similar choice when it was present in the Distractor condition (see dashed line in Figure 6). However, the HK sample showed no decline in performance for 2-Relation problems relative to US children, and outperformed US children on the 2-Relation problems. This was true for both the 3-year-olds and 4-year-olds when examined separately. This reinforced our contention that these children may have a more expert, or at least a different, representation of the relational knowledge (verbs) needed to solve these multi-relation scene analogy problems. In order to ensure that the linguistic translation of the task could not have explained the differences, an additional control condition was run with 3- and 4-year-old US children using a back-translation of the Cantonese version, and the results replicated the prior US children's data (Richland *et al.*, 2010). The Chinese sample again outperformed the US sample on 2-Relation problems.

Simulating United States children's analogical reasoning

We simulated children's performance in the scene analogy problems to demonstrate that a systematic change in inhibition levels in LISA could account for age-related distraction and relational complexity performance changes in analogical reasoning. To model the scene analogy problems, we constructed LISA representations of the four problem types. 1-Relation problems were represented by a single, 2-place predicate (e.g. *chase1* (cat, mouse); see Figure 4ai). For 2-Relation problems we represented both target relations explicitly as two, 2-place predicates (e.g. *chase2* (dog, cat) and *chase1* (cat, mouse); see Figure 4aii). [1] As such, both relations were represented in LISA's working memory together. Thus, the 2-relation phase set (i.e. the number of SPs and their attached Predicate and Object units that must fire independently to represent the full relational structure in working memory; see Figure 4bi & 4bii) was double that of the 1-Relation phase set. In LISA, units of the same type in the driver and recipient inhibit one another (i.e. SPs inhibit other SPs, Ps inhibit other Ps, etc.). In fact, it is this inhibition that allows the various SPs in the phase set to have an opportunity to timeshare in working memory. To simulate each age group we changed the

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[1] While we hand-coded these representations to clearly embody our hypothesis in this study, they could have been generated using DORA (Doumas *et al.*, 2008) from unstructured examples of chasing between objects. See Doumas, Morrison and Richland (2010).

inhibition level between corresponding units in the driver and the recipient. Younger age groups were assigned lower mean inhibition levels.

Each simulation run consisted of firing three phase sets in LISA's working memory, 'randomly' assigned by LISA. On each simulation an inhibition level for units in the recipient was sampled from a normal distribution with the means listed in Figure 7 and an SD of .1. The inhibition between corresponding units in the driver and recipient were set to the inhibition level. We ran 40 simulations of each problem type for each age group. When LISA failed to determine a stable mapping after firing three phase sets, an answer was selected based on Equation 1:

$$C_i = \begin{cases} \frac{1+w_{ij}}{n}, & w_{ij} > \max(w_{kj}) \\ \frac{1-\max(mapWeight)}{n}, & otherwise \end{cases} \quad (eq.1)$$

where w_{ij} is the mapping weight from recipient unit i to driver unit j, $\max(w_{kj})$ is the maximum mapping weight into all other recipient units k, where k is the same type as i, to driver unit j, $\max(mapWeight)$ was the highest mapping weight into any recipient object unit and driver unit j, and n is the number of object units in the recipient, and the probability, P_i, of selecting any recipient unit i, was given by:

$$P_i = \frac{C_i}{\sum_j C_j} \quad (eq.2)$$

where j is all units of the same type as i in the recipient (including unit i).

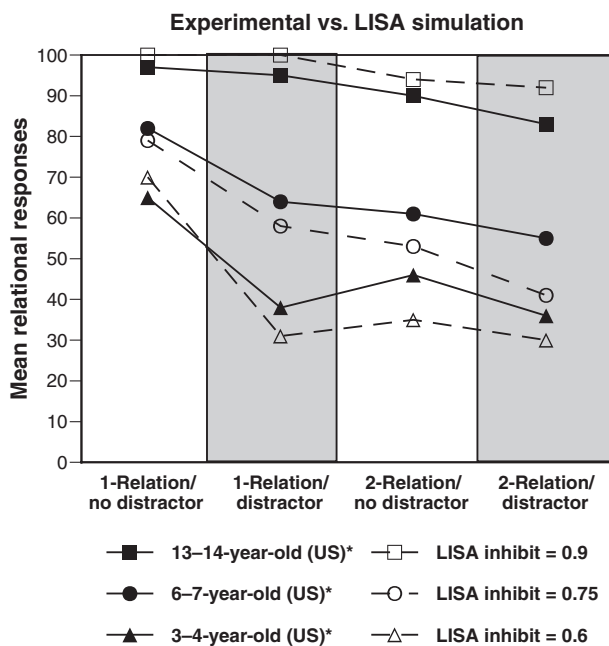**Experimental vs. LISA simulation**

Figure 7 *Comparison of experimental and LISA simulation results.* Change in performance of the scene analogy problems by US children is well fit by progressively increasing inhibition in LISA to simulate older children.

The simulation results along with the experimental results from Richland *et al.* (2006) are presented in Figure 7. LISA's performance mirrored experimental results for each age group across conditions, accounting for a large portion of the variance in the experimental results ($R^2 = 0.97$) with just a single parameter change. Specifically, LISA simulations showed: (1) a main effect of age, (2) an effect for both relational complexity and distraction for 3–4-year-olds, (3) a smaller effect for both relational complexity and distraction for 6–7-year-olds than for 3–4-year-olds, and finally (4) a mild effect for relational complexity, but no effect for distraction for 13–14-year-olds.

Lowering the inhibition between units in LISA's driver and recipient produced patterns of behavior that very closely resembled the age-related differences in analogical ability exhibited by human children. When there is less inhibition in the driver, LISA's working-memory efficiency is decreased because units that had just been active are more likely to fire again immediately (because of their high level of activation), thus firing is less systematic. When there is less inhibition between units in the recipient, there is decreased competition between these units to respond to patterns of activation in the driver. With less competition, more recipient units became active simultaneously, which impeded LISA's ability to find the accurate mapping between source and target items (i.e. as each role and filler in the driver activated more numerous roles and fillers in the recipient, it was more difficult for LISA to determine which recipient units the active driver units corresponded to).

Lastly, as in the experimental results, when LISA did not select the correct analogical mapping in the distractor conditions, the model preferentially chose the featurally similar distractor object. This was due to the distractor object in the recipient (e.g. sitting cat) sharing the most semantic units with the indicated object in the driver (e.g. running cat) and thus the distractor was the most likely object to be active via spreading activation.

Interestingly, decreasing inhibition levels captured the effects of both distraction and relational complexity and the interaction between them mimicking the exact pattern observed in human children. While distraction and relational complexity effects are sometimes thought of as distinct effects, these simulations suggest that there may be a single underlying neural cause of these patterns of results, that is, limited inhibition between units.

Simulating Hong Kong children's analogical reasoning

HK 3–4-year-old children performed better on 2-relation, No-Distractor problems than US children (Richland *et al.*, 2010). One explanation for this might be that HK 3–4-year-olds had greater working-memory capacity than US children and this allowed them to more efficiently process the more relationally complex problem. While some early evidence seemed to suggest differences in working-memory capacity between Western and Eastern

children, these differences have typically been explained in terms of differences in phonetics in very limited situations (see Baddeley, 1996). An alternative explanation is that HK children utilized a more efficient relational representation that minimized processing demands, thus allowing for greater success on two-relation problems in spite of similar processing capacity to US children of the same age. This may have been facilitated by their greater experience with representing relations and producing verb phrases. At this point we are not prepared to try and differentiate between potential causes for a child's increased ability to represent relations, but the difference in a child's mental representations could explain his/her seemingly greater ability to solve complex, multi-relation analogies. Relational representation should not impact susceptibility to object distraction, however, since in these stimuli the object distractor was not a part of the relational group in the stimuli. Thus, we hypothesized that the 3–4-year-old Cantonese speakers would continue to show decrements in performance related to the object similarity distractor.

To test this hypothesis, we modeled 2-relations problems in LISA using a single three-place proposition (i.e. *chase* (dog, cat, mouse)) instead of the two binary propositions (i.e. *chase1* (dog, cat); *chase2* (cat, mouse)) we used in modeling US children's performance (see Figure 4aiii). In LISA, this change in representation results in only three role-bindings needing to be fired out of synchrony as opposed to the four role-bindings necessary for two binary propositions. Thus, the demands on LISA's working memory are lower and, correspondingly, inhibition is less critical. Experimental results for 3–4-year-old children from both countries and the simulation results for both representations run at a low inhibition parameter setting (i.e. 0.6) are shown in Figure 8. While a two-binary relational representation scheme better fits US children's performance, a single-ternary relational representation scheme better fits HK children's performance.

Discussion

In this paper we have presented simulations in LISA that support the hypothesis that maturation of inhibitory control in working memory is critical for the development of adult-like analogical reasoning. Specifically, we demonstrated that simple changes in inhibition levels in LISA (i.e. inhibition between elements of competing relational representations in working memory) could account for both relational complexity and featural distraction effects in children's analogical reasoning performance from age 3 to 14 (Richland *et al.*, 2006). This account is consistent with previous simulations of results from frontal patients (Morrison *et al.*, 2004) and older adults (Viskontas *et al.*, 2004) whose analogical reasoning performance also suffered under increases in relational complexity and featural or relational distrac-
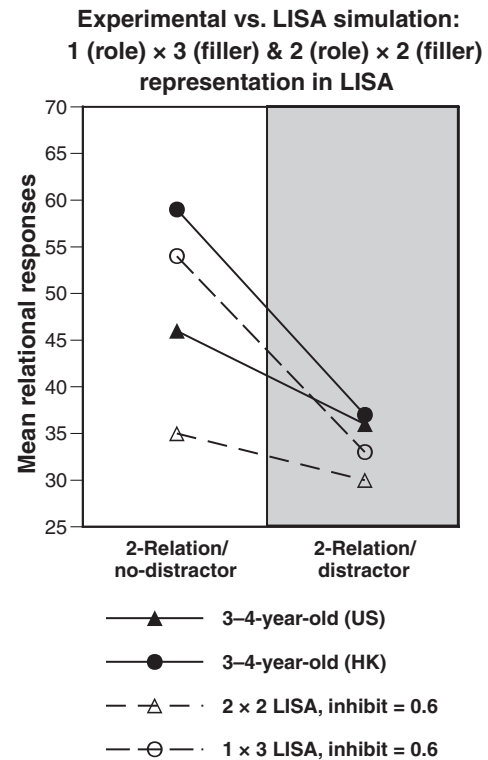

Figure 8 *Comparison of experimental and LISA simulation results. US 3–4-year-old children's performance on 2-Relation problems is better fit in LISA by using a representation consisting of two binary (i.e. 2 (role) × 2 (filler)) propositions, while HK 3–4-year-old children's performance is better fit in LISA by using a representation consisting of one ternary (i.e. 1 (role) × 3 (filler)) propositions.*

tion. Given that inhibition is critical for maintaining systematic patterns of temporal synchrony (and asynchrony) in LISA, this result is also consistent with recent evidence suggesting that task-related neural synchrony as measured via EEG increases during childhood and adolescence (Uhlhaas, Pipa, Lima, Melloni, Neuenschwander, Nikolić & Singer, 2009).

Second, we presented simulations in LISA that demonstrate how relational knowledge acquisition and inhibitory control in working memory can interact during development. Specifically, we demonstrated that a knowledge representation change from two, 2-place predicates into one, 3-place predicate reduces the demands of processing a '2-relation' scene analogy problem in LISA. This simulation thereby offers an explanation why Hong Kong children perform better on 2-Relation analogy problems than United States children while still showing object featural-distraction effects at the lower inhibition levels used to model 3–4-year-olds. It is important to note that an explanation solely based on relational knowledge acquisition is inadequate to explain these experimental results because both relational complexity and object featural distraction did not improve in the Hong Kong children together.

These simulations in LISA are based on a number of assumptions about the basic cognitive abilities of young

children. Specifically, we assume that young children are capable of learning and mapping explicit relations (e.g. Chen *et al.*, 1997; Gentner & Rattermann, 1991; Goswami, 1992, 2001). We also assume that their working memory/executive functions are limited – an assumption that been been supported by many experimental studies (see Diamond, 2002; Fuster, 2008). They also avoid the issue of how children discover relations and how they recognize these relations in a particular scene. The solution to the problem of relation discovery has recently been offered by Doumas *et al.* (2008) in a model that generates relational knowledge structures in the form used by LISA from real-world unstructured examples. The second issue, how reasoners decide which relations to attend to, is an ongoing topic of study. In these simulations we simply represent the relations which children describe when asked what is going on in the scene. These include the relational and featural knowledge structures.

It is our contention that both relational knowledge acquisition and inhibitory control in working memory can shape an individual's analogical reasoning performance. We suggest that the development of analogical reasoning in children can be conceptualized as an equilibrium between these two factors. In particular, as children age, their knowledge about relations advances while their working-memory capacity as modulated by inhibitory control also improves. At a given time during development, the child is able to perform an analogical task based on both their level of relational knowledge and their working-memory resources. Specifically, the equilibrium operates such that greater relational knowledge can impose fewer processing demands while less knowledge imposes higher demands. Thus, Hong Kong children given the same working-memory resources can better solve relationally complex problems. More generally, as relational knowledge increases in a domain, the demands on working memory decline, allowing for more complex reasoning at any given age. This pattern in cognitive development builds on an understanding of working-memory effects in expertise (e.g. Chase & Simon, 1973) where advanced relational knowledge can decrease processing demands and thereby allow experts to accomplish cognitive tasks which novices cannot.

We believe that to truly understand the development of relational reasoning in children, future experimental and computational studies must take into account both advances in relational knowledge and changes in inhibitory control in working memory. In particular, we posit that better understanding of how these two aspects of development interact is essential to clarifying the developmental course of relational reasoning.

Acknowledgements

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