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# The Role of Working Memory in the Subsymbolic–Symbolic Transition

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**Abstract**

In this article, a proposal is made for a new account of the subsymbolic-to-symbolic transition based on a contemporary conception of working memory. Symbolic cognition is a constituent of reasoning and language and requires an operating system that is flexible and can produce novel, yet coherent, representations of relations that are useful in adapting to the environment. Acquisition of such an operating system depends on dynamic binding to a coordinate system in working memory. Recent studies with infants have indicated that this ability develops late in the 1st year of life, which corresponds to the time when symbols emerge in infant cognition. It also corresponds to the time when infants cease to make the A-not-B error, which depends on dynamic creation of a link in memory between an object and its location in space. We propose that such dynamic binding is a previously unrecognized marker of the symbolic transition. Emergence of symbolic processes (e.g., language, theory of mind) should be predicted longitudinally by dynamic binding to a coordinate system.

**Keywords**

subsymbolic-to-symbolic transition, working memory, dynamic binding, A-not-B error

The transition from subsymbolic to symbolic cognition (the *symbolic transition*) is inherently important because it enables the abstract thought that is vital to our culture. Three major areas of research have converged recently in a way that enables a new approach to the symbolic transition. These areas are research on infant cognition (Cohen & Cashon, 2006; Wellman, 2011), the theory of relational knowledge (Dixon & Kelly, 2007; Doumas, Hummel, & Sandhofer, 2008; Goodwin & Johnson-Laird, 2005; Halford, Wilson, & Phillips, 2010; Kokinov, Holyoak, & Gentner, 2009), and a theory that dynamic binding to a coordinate system is a component of working memory (Oberauer, 2009). Dynamic binding depends on activation of bound elements and is not based on enduring links, such as those that comprise semantic memory. Thus, remembering where we placed an object a moment ago and remembering the temporal order of two recent events are examples of dynamic binding. Dynamic bindings can also be reformed rapidly, as when, for example, we reassign an event to a different position in a temporal order.

The essence of our proposal is that symbols require an operating system based on relational knowledge, which depends on working memory. Therefore, we should look for the origins of symbolic cognition in dynamic binding to a coordinate system. There is considerable developmental evidence relevant to dynamic binding between objects and their locations, but the significance of this research for the symbolic transition has not previously been recognized.

## Symbols

Cognitive symbols (henceforth *symbols*) are representations that support adaptation to the environment, but symbols have additional properties that enable them to play a central role in higher cognition, including reasoning and

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language. Symbols can be defined by convention, as with words and mathematical symbols, but they can also be idiosyncratic, as with, for instance, an infant's gesture to represent a size difference between objects. The properties of symbols have been considered by many authors (see reviews by Halford et al., 2010; Penn, Holyoak, & Povinelli, 2008); in particular, Evans (2008) has provided a broader review of levels of cognition. The properties of symbols that are most relevant to our proposals include compositionality. For example, we can compose *brown* and *dog* to yield *brown dog*, but the components retain their respective identities in the combination.

A distinguishing feature of symbols is that they are bound to roles. For example, in the sentence *John loves Mary*, John is bound to the lover role and Mary to the loved role. Thus, we can understand *Mary loves John* because we can reassign Mary and John to lover and loved roles, respectively. Compositionality and role binding enable structures and meanings to be built up from simpler components, a process that is essential to the compositional syntax and semantics that are at the core of symbolic thought and language (Halford et al., 2010).

Symbols depend on an operating system that gives them meaning, so symbols are *processor relative* (A. Clark, 1992, p. 193). For example, number symbols are given meaning because they can be assigned to sets with a given number of elements—*1* is assigned to sets with a single element, *3* to sets of three elements, and so on. It is important to note that relations between sets correspond to relations between numbers. For example, 3 is a bigger number than 1, and a set of 3 is larger than a set of 1. Thus, symbols are embedded in structures that comprise relations between entities and give symbols meaning. Relations provide a basis for the operating system that underlies reasoning, categorization, and language (Gentner, 2010; Goodwin & Johnson-Laird, 2005; Halford et al., 2010; Holyoak, 2005). Propositions, which play a major role in symbolic cognition, can be represented as instances of relations. For example, *John loves Mary* is a proposition, and is an instance of the loves relation. The symbolic transition is closely linked to acquisition of relational knowledge because it provides the basis of an operating system for symbols.

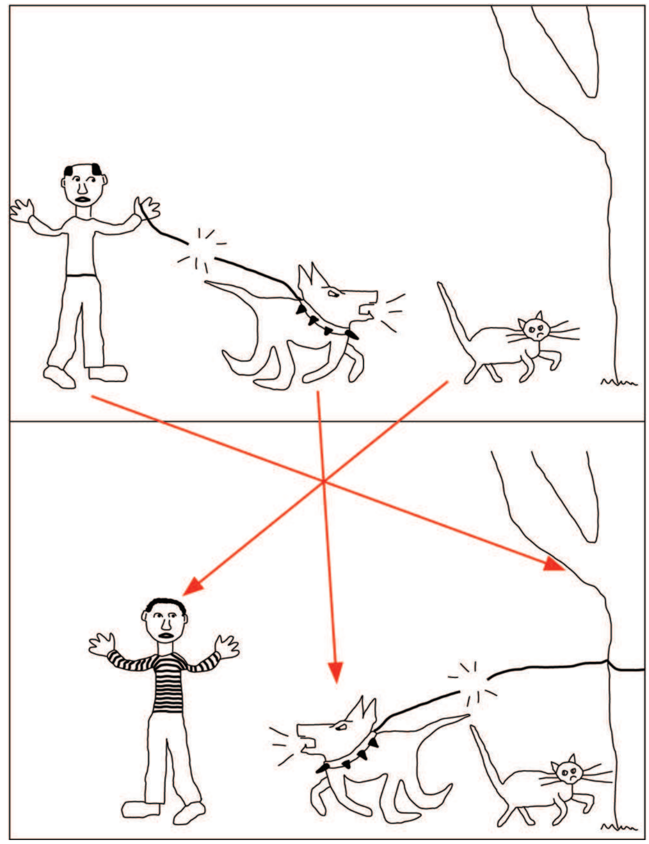

**Fig. 1.** A picture-based analogy. In the top picture, a man restrains a dog that chases a cat. In the bottom picture, a tree restrains a dog that chases a boy. *Man, dog*, and *cat* are cross-mapped to *tree, dog*, and *boy*, respectively, and *restrains* and *chase* in the first picture are mapped to the corresponding relations in the second picture. Adapted from "The Impact of Anxiety on Analogical Reasoning," by J. M. Tohill and K. J. Holyoak, 2000, *Thinking & Reasoning, 6*, p. 31. Copyright 2000, Taylor & Francis. Adapted with permission.

## Relational Knowledge and Reasoning

The importance of relational knowledge to reasoning is demonstrated by research on analogies, which play a role in many kinds of cognition (Kokinov et al., 2009). An example would be an analogical mapping task based on two pictures as shown in Figure 1.

Transitive inference is fundamental to reasoning (James, 1890) and can be performed by constructing symbolic representations in working memory (Halford et al., 2010), as shown in Figure 2. This process imposes a load on working memory (Halford, Wilson, & Phillips, 1998; Maybery, Bain, & Halford, 1986; Waltz, Lau, Grewal, & Holyoak, 2000) that depends on the complexity of the relations. The first relational knowledge to emerge in infancy is knowledge of unary relations, which comprise a binding between a symbol and an entity. Examples include labeled categories—for instance, *dog*, which is bound to instances, such as *Fido*, and to attributes such as *large*. In general, unary relations correspond to one-place predicates that apply to one entity (e.g., *large* in *Fido is large*), whereas binary relations correspond to two-place predicates because they apply to two entities (e.g., *larger* in *The dog is larger than the cat*).

## Working Memory as a Prerequisite for Symbolic Processes

Aggregated measures of working memory account for a high proportion of variance in reasoning (Kane et al.,

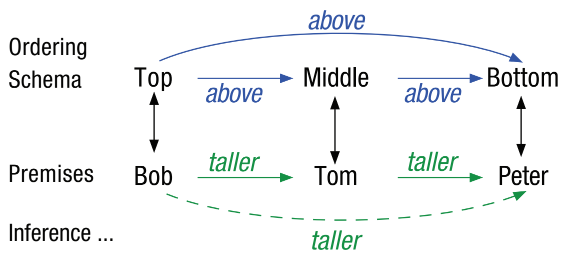


**Fig. 2.** Transitive inference made by constructing a representation in working memory. Premises *Tom is taller than Peter* and *Bob is taller than Tom* are mapped into the ordering schema *top above middle above bottom*, such that Bob, Tom, and Peter are assigned dynamically to the top, middle, and bottom positions, respectively. This creates a new representation in which Bob, Tom, and Peter are ordered by height and enables the transitive inference *Bob is taller than Peter*.

2004), and the theory of working memory must be at the core of our argument. Oberauer (2009) has proposed that the central component of working memory is dynamic binding of elements to a coordinate system to form new structures. In one working memory test, Oberauer (2005) presented sets of two to five words, each in a different frame on a screen. A local recognition test, in which participants judged whether probe words appeared in the same frame they had appeared in previously, assessed binding of words to frames. This binding was a better predictor of working memory capacity, assessed by a battery of tests, than was memory for words regardless of the frame in which they occurred. The words were bound in memory to a coordinate system comprising frames that were linked by a left-right spatial relation. However, nonspatial coordinate systems can also be used, such as positions in the alphabet, in a musical scale, or in social-dominance hierarchies.

We propose that the symbolic transition depends on dynamic binding to a coordinate system in working memory. The symbols are activated representations in declarative memory that are in the focus of attention and can be dynamically bound to slots in a coordinate system. The dynamic-binding function provides the flexibility that is required in symbolic cognition and therefore should play a role in the emergence of symbolic processes. If so, then we should be able to detect the onset of symbolic processes in infants on the basis of whether they can dynamically bind elements to a coordinate system.

## Development of Dynamic Binding to a Coordinate System

There is evidence that dynamic binding to a coordinate system develops rapidly in the 1st year of life. Binding between attributes of the same object, such as shape and color, appears to be possible at or soon after birth (see review by Oakes, Ross-Sheehy, & Luck, 2006). Bindings between objects and other entities develop gradually through the 1st year. Before about 4 months, following occlusion, infants can recall objects, or locations, but not the binding between them (Mareschal & Johnson, 2003). A study of crucial relevance (Kaldy & Leslie, 2003) has shown that binding between objects and locations is evident at 9 months. In this study, the location of objects was varied from trial to trial, to avoid associations between object attributes and locations. Two objects were placed behind spatially separated screens while infants watched. When the screens were lowered, infants looked longer at displays where the objects had been switched, which indicates that they had represented the binding between each object and its location. Thus, binding of objects to locations appears to develop later than binding of attributes within one object. More advanced object-location bindings have been observed at 11 months (Feigenson & Yamaguchi, 2009; Leslie & Chen, 2007). Development from 4 to 6 years of age has been observed in binding animals to locations (Sluzenski, Newcombe, & Kovacs, 2006) and objects to backgrounds (Lloyd, Doydum, & Newcombe, 2009).

These object-location tests assess dynamic bindings to a coordinate system consisting of a set of locations in space. Because spatial cognition develops early, dynamic binding to spatial locations provides an efficient way to begin the formation of structured representations (Piazza, 2010). Mapping to a spatial representation can be used to construct new representations in reasoning later in childhood and adulthood, as illustrated by the transitive-inference task discussed earlier.

To summarize, dynamic object-location binding develops late in the 1st year and lays the foundation for the transition to symbolic processes. However, research on a classic task sheds further light on dynamic creation of representations in the 1st year.

### *Overcoming the A-not-B error*

In the classic A-not-B task, infants between 7 and 12 months of age who have retrieved a hidden object a number of times from Location A tend, on seeing it hidden at Location B, to search for it at *A*. Established empirical observations include effects of age, number of retrievals from Location A, and the effect of labeling, delay, and the number and distinctiveness of hiding locations (Marcovitch & Zelazo, 1999). We propose that infants cease to make the A-not-B error when they can dynamically bind a representation of an object to a representation of its location in a coordinate system. Given the dependence of symbols on relational knowledge, this achievement means that the A-not-B task has previously unrecognized significance as a marker of the onset of symbolic processes.

The hierarchical competing systems model of Marcovitch and Zelazo (2009) accounts for the A-not-B task as a competition between a *habit system* and a *representational system*. The habit system reflects an association that causes the infants to perseverate in reaching toward Location A, despite seeing the object hidden at Location B, whereas the representational system is attributed to conscious reflection on the object being at Location B, but we interpret it in terms of dynamic working memory processes. Cooper (2009) has noted consensus that there is a lower cognitive system and a later-developing higher cognitive system. Diamond (2009) has proposed that inhibitory control of the habit system is necessary, but there are relational knowledge processes that can switch between alternative representations, thereby inhibiting one of the representations (Halford et al., 1998). Smith (2009) has proposed that the representational system could result from dynamic interaction of existing representations with a new sensory input resulting from seeing the object being hidden at Location B. This account is consistent with a mechanism based on dynamic binding in working memory between the new seen location of the object (new input) and existing semantic memory of the previous location, as proposed by Oberauer (2009).

We interpret the representational system in terms of Oberauer's (2009) working memory model: as a dynamic binding in memory between an object and a location. We need to explain not only the error but how the error is overcome. We propose that infants cease to make the A-not-B error when they can form a representation of an object and dynamically connect it to a representation of its location. Our interpretation of the working memory process required to overcome the A-not-B error is shown in Figure 3. The habit, formed by successive retrievals at Location A, is overcome by mapping the representation of the object into a coordinate system comprised of the set of hiding locations and the spatial relations between them. That is, the error will cease to be made when the infants have a dynamic capability for object-location binding. In our interpretation, they are demonstrating an early ability to dynamically create new symbolic representations that comprise a link between an object and a location. This is arguably a primitive case of the dynamic binding that occurs in binding a filler to a role, the role being the representation of a location in space and the filler being the representation of the object. This role-filler binding is equivalent to a newly-formed unary relational representation.

Thus, although many factors influence performance on the A-not-B task, we propose that it depends in part on dynamic binding in working memory of objects to locations. The tendency to continue attempting to retrieve the object from Location A, despite seeing it hidden at Location B, is a triumph of behavioral mastery over newly developing, but still relatively weak, dynamic binding to a coordinate system. Cessation of the A-not-B error represents the triumph of symbolic processes over associative learning. Thus, correct performance of the A-not-B task is tantamount to construction of a new representation, comprising a binding between an object and a location. This explanation implies that correct performance should be related to emerging symbolic processes.

## Onset of Symbols

Dynamic binding to a coordinate system precedes rapid acquisition of symbolic processes, as exemplified by a number of cognitive attainments, most notably in language and theory of mind. The use of words with recognition of their meaning typically occurs early in the 2nd year (E. V. Clark, 2003). Verb acquisition (Golinkoff & Hirsh-Pasek, 2008) entails relational knowledge because verbs are fundamentally relational. For example, verbs expressing actions, such as *pulls* in the sentence *Tommy pulls his wagon*, represent relations between agent (in this case, Tommy) and object (wagon). Therefore, onset of verb acquisition should be predicted by measures of dynamic binding to a coordinate system, including object-location binding and overcoming of the A-not-B error. However, nouns are also relational, in that they fill roles—such as the role of agent and the role of object—in sentence frames and are assigned to meanings that are embedded in events and situations. Ceasing to make the A-not-B error should portend the growth of symbolic processes, including acquisition of word meanings.

Another acquisition in infancy for which there is extensive evidence is theory of mind (Baillargeon, Scott, & He, 2010; Sodian, 2011). In the commonly used false-belief task, an infant is required to interpret a sequence such as the following: An agent sees a toy hidden in a green box, then leaves, and the toy is moved to a yellow box without the agent's knowledge. The child knows that the toy is in the yellow box, but the agent falsely believes that the toy is in the green box. The agent returns and searches for the toy. Understanding that the agent has a false belief is indicated by greater surprise (more time spent looking) when the agent searches in the yellow box, but interpretations of infant data are controversial. The infants could be representing awareness (Wellman, 2011), which entails a (binary) relation between the agent and the object in the green box. This is a simple form of symbolic reasoning that is possible in the 2nd year of life (Andrews & Halford, 2002) and should be predicted by dynamic binding to a coordinate system. More complex theory-of-mind tasks require representation of a ternary relation among three variables: the original hiding location (the green box in the example), occurrence or

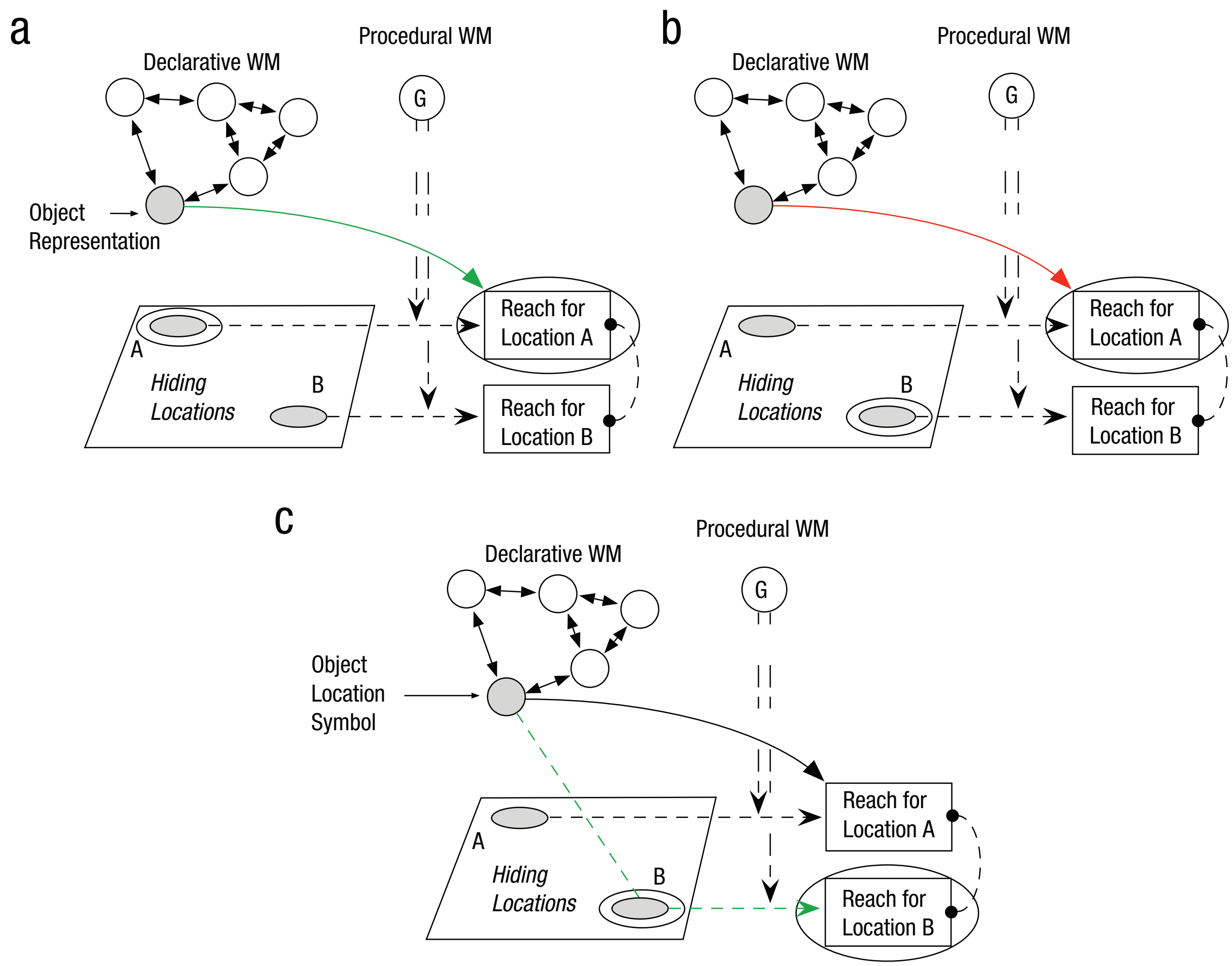


**Fig. 3.** Application of the working memory model of Oberauer (2009) to the A-not-B error. All diagrams depict situations following a number of trials in which the object has been retrieved from Location A. The goal (G) is to reach for the object where it is believed to be. In panel (a), the object is hidden at Location A: A representation of the object is activated in declarative working memory, and there is an association (indicated by the green arc) with reaching for the object at Location A, which is correct. In panel (b), the object is hidden at Location B, the association (indicated by the red arc) with reaching to Location A is still present, and there is no dynamic binding between the object and Location B. Therefore, the association dominates performance and the A-not-B error occurs. In panel (c), the A-not-B error is not present: There is a dynamic binding (indicated by the dashed green line) between the object and Location B. Influenced by the goal, the motor program to reach for Location B is activated, so the correct choice is made: to reach for Location B. Small circles represent elements of declarative working memory and shaded circles represent activation above baseline. Dashed lines without an arrow represent dynamic bindings, solid lines with arrows represent associations, and solid lines with black knobs represent inhibitory connections between reaching for Location A and reaching for Location B. WM = working memory. Adapted from Oberauer (2009) Figure 4. Adapted from "Design for a Working Memory," by K. Oberauer, 2009, in B. H. Ross (Ed.), *The psychology of learning and motivation: Advances in research and theory* (pp. 45–100), p. 58. Copyright 2009, Elsevier. Adapted with permission.

nonoccurrence of removal, and the new hiding location (the yellow box). Consequently, ability to perform the task is not attained until approximately 5 years of age, when other ternary relational concepts are acquired (Andrews, Halford, Bunch, Bowden, & Jones, 2003).

## Conclusions

The optimal way to investigate the conceptual link between dynamic binding and the symbolic transition would be through longitudinal studies of subjects from 6 to 60 months of age. Our theory implies that symbolic processes, including theory of mind and word acquisition, should be predicted by ability to perform dynamic-binding tasks, including the object-location task of Kaldy and Leslie (2003) and the A-not-B task. These predictions should be maintained after controlling for age-related variance shared in performance of nonsymbolic tasks in the same domain, thereby excluding the possibility that they reflect only age-related changes. Studies of infant language and theory of mind have not included tests of dynamic binding, presumably because these processes have not been recognized as relevant to the symbolic transition. However, there clearly is potential to find links that could offer a whole new approach to the profound problem of how we acquire symbolic processes.

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## Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

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