A Brain-Based Account of the Development of Rule Use in Childhood

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ABSTRACT—*The ability to follow explicit rules improves dramatically during the course of childhood, but relatively little is known about the changes in brain structure and function that underlie this behavioral improvement. Drawing from neuroscientific studies in human adults and other animals, as well as from an emerging literature in developmental cognitive neuroscience, we propose a brain-based account of the development of rule use in childhood. This account focuses on four types of rules represented in different parts of the prefrontal cortex: simple rules for reversing stimulus–reward associations, pairs of conditional stimulus–response rules (both univalent and bivalent), and higher-order stimulus–response rules for selecting among task sets. It is hypothesized that the pattern of developmental changes in rule use reflects the different rates of development of specific regions within the prefrontal cortex.*

KEYWORDS—*cognitive control; executive function; task set; complexity; neuroimaging*

The use of explicit rules to control behavior is one of the hallmarks of executive function—the conscious control of thought, action, and emotion—and it develops gradually over the course of childhood. As children get older, they typically become increasingly adept at using explicit rules to solve problems, play games, and interact with others. Behavioral research has now established that the development of rule use follows a reliable pattern: Children first acquire the ability to use a single rule, then the ability to switch flexibly between two rules, and then the ability to switch flexibly between two incompatible pairs of rules (Zelazo, Muller, Frye, & Marcovitch, 2003). The neural correlates of these developmental changes are not yet well understood, mainly because until recently there were no measures of brain function suitable for use in young children. But given what is known about the neural basis of rule use in human adults and nonhuman primates, together with what is known about the growth of the prefrontal cortex (PFC) in childhood and adolescence, we propose a brain-based account of the development of rule use in childhood. Although this brief overview focuses on the role of the PFC, other brain regions are also needed to represent rules and implement them flexibly (Bunge, 2004).

THE PREFRONTAL CORTEX

The PFC is a large expanse of cortex at the front of the brain that has been closely associated with rule use in human adults and nonhuman animals. Through its interactions with numerous other brain regions, the PFC processes information about an individual's current context and about his or her goals and motivations. The PFC also plays an important role in retrieving rules for governing behavior in the current context—for example, the rule that if one is sitting in a classroom, one should raise one's hand to be excused. The involvement of the PFC is particularly important when rules are not yet overlearned or automatic and when ad hoc rules must be formulated to govern behavior in an unfamiliar setting. Indeed, patients with damage to the PFC have particular difficulty planning and controlling their behavior when faced with novel challenges.

The PFC consists of a number of subregions, including the orbitofrontal, ventrolateral, dorsolateral, and rostrolateral prefrontal cortices (Fig. 1). Evidence that these regions have different functions comes from several sources. First, structural investigations reveal that these regions differ in their cellular composition and in their connections to other brain regions. Second, neuropsychological studies in humans and focal-lesion

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(selective removal) experiments in nonhuman primates reveal different cognitive deficits following damage to each of these regions. Finally, brain-imaging experiments in school-aged children and adults, using techniques like functional magnetic resonance imaging (fMRI), show that these regions are engaged differently for different kinds of cognitive demands.

PREFRONTAL REGIONS AND RULE COMPLEXITY

A growing body of evidence indicates that the different regions of the PFC are involved in representing rules at different levels of complexity—from single rules for new stimulus–reward associations (orbitofrontal cortex), to sets of conditional rules (ventrolateral and dorsolateral PFC), to task sets (rostrolateral PFC; see Fig. 1).

Orbitofrontal Cortex: Stimulus–Reward Associations

From infancy onward, individuals learn that some stimuli (such as a high chair) are associated with rewarding experiences, and others (such as a pediatrician's office) with experiences that are perceived to be detrimental or less rewarding. These associations need not be represented explicitly (i.e., an individual need not be conscious of them). However, if there is a sudden change in the outcome associated with a stimulus, it may be helpful to represent the new stimulus–reward association explicitly. In humans, the ability to reverse stimulus–reward associations improves dramatically during the first 3 years of life (Overman & Bachevalier, 1999). Although the hypothesis has yet to be explicitly tested, this improvement is likely to be related to structural changes in the orbitofrontal cortex. The ability to reverse stimulus–reward associations is impaired by damage to the orbitofrontal cortex in both human adults and nonhuman primates (e.g., Rolls, Hornak, Wade, & McGrath 1994; Dias, Robbins, & Roberts, 1996).

Electrophysiological findings in nonhuman primates indicate that orbitofrontal neurons encode the values of rewards associated with specific stimuli and strongly suggest that this reward information is passed on to dorsolateral prefrontal neurons, which then select a response on the basis of this information (Wallis & Miller, 2003). In contrast to its crucial role in representing single stimulus–reward associations, the orbitofrontal cortex does not appear to have to update rules that do not explicitly assign a value (amount of reward or punishment) to a stimulus (e.g., one might learn that an apple is a rewarding stimulus whereas broccoli is an unrewarding stimulus), as in the conditional stimulus–response rules discussed below (Dias et al., 1996).

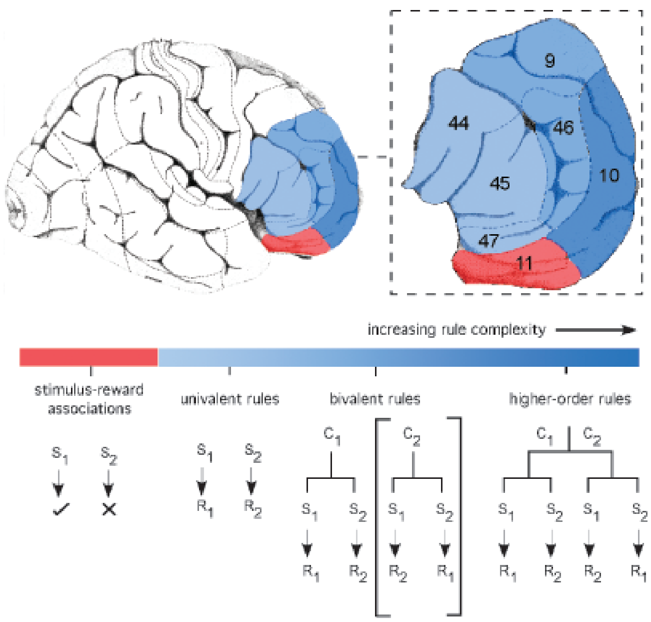

Fig. 1. A hierarchical model of rule representation in the lateral prefrontal cortex (PFC). A lateral view of the human brain is depicted at the top of the figure, with regions of the PFC identified by different Brodmann areas (BA): the orbitofrontal cortex (BA 11), the ventrolateral PFC (BA 44, 45, 47), the dorsolateral PFC (BA 9, 46), and the rostrolateral PFC (BA 10). Rule structures are shown below along a continuum from simple to complex, in colors corresponding to the brain regions that represent them. S = stimulus; check = reward; cross = nonreward; R = response; C = context, or task set. Brackets indicate a bivalent rule that is currently being ignored. The lateral PFC regions are shown in various shades of blue, with darker shades indicating regions that represent more complex rules. The orbitofrontal cortex is shown in red, to indicate that the rules represented in this region are qualitatively different from the types of rules represented in the lateral PFC, in that the rules provide information about the value of a stimulus. (Differences between the medial and the lateral orbitofrontal cortex with respect to the representation of rewards and punishments are not depicted here.)

The Ventrolateral and Dorsolateral PFC: Sets of Conditional Rules

The simplest set of conditional rules consists of a pair of *univalent* stimulus–response associations—rules in which each stimulus is associated with a different response. For example, drivers learn to associate a green light with driving and a red light with stopping. More complex rule sets involve *bivalent* conditional rules, or rules in which two different responses may be associated with a single stimulus, depending on the context in which the stimulus occurs.

Neuroscientific studies implicate both the ventrolateral and dorsolateral PFC in the representation of sets of conditional rules, although the precise roles of these regions may differ (for a review, see Bunge, 2004). Lesion studies in nonhuman primates show that the ventrolateral PFC is critical for learning pairs of univalent and bivalent conditional rules. fMRI studies in humans show that both the ventrolateral and dorsolateral PFC are active during the maintenance (i.e, keeping in mind) of sets of conditional rules, and that they are sensitive to rule complexity. Specifically, these regions are more active when participants consider stimuli that have been associated with different responses depending on the rule relevant to the current context (bivalent stimuli) than when they consider stimuli with fixed responses (univalent stimuli; Crone, Wendelken, Donohue, & Bunge, 2006). These regions are also more active for more abstract conditional rules (e.g., "match" or "non-match" rules, whereby different actions are required depending on whether two objects match or not) than for rules representing specific stimulus–response associations (Bunge, Kahn, Wallis, Miller, & Wagner, 2003). However, the dorsolateral PFC is particularly engaged when participants must switch from one bivalent rule to another and hence suppress the previously relevant rule (Crone, Wendelken, et al., 2006). Thus, in studies of humans and non-human primates, the ventrolateral PFC is consistently involved in representing sets of conditional rules, suggesting that it plays a fundamental role in rule representation, whereas fMRI data suggest that the dorsolateral PFC may be especially important for overcoming interference from previously learned rules.

Rapid changes in flexible rule use between 2 and 5 years of age may reflect the growth of these lateral regions of the PFC. Two-year-olds have difficulty using a pair of arbitrary rules (e.g., things that make noise vs. things that are quiet) to sort a series of items: They tend to perseverate on a single rule. By 3 years, children can represent a pair of rules and use them contrastively (Zelazo & Reznick, 1991). However, they have difficulty switching between two incompatible pairs of rules, as in the Dimensional Change Card Sort (DCCS), which requires them to match bivalent test cards (e.g., red rabbits and blue cars) to target cards (e.g., a blue rabbit and a red car) first by one dimension and then by the other (e.g., shape then color). Regardless of which dimension is presented first, 3-year-olds typically continue to sort the cards by that dimension despite being told the new rules on every trial (Zelazo et al., 2003).

Rostrolateral Prefrontal Cortex: Explicit Consideration of Task Sets

Switching from one type of task to another—for example, switching from sorting by shape to sorting by color in the DCCS—arguably involves some skill in addition to the ability to use one pair of rules while resisting interference from a similar but incompatible pair; it also requires the explicit representation of a higher-order rule for selecting among task sets, or ways of approaching the problem (e.g., selecting whether to sort by shape or color). In other words, it requires reflection on task sets per se—one needs to consider the task sets explicitly. These two abilities, while clearly distinct, are closely intertwined and develop together in early childhood and beyond (e.g., Zelazo et al., 2003; Zelazo, Craik, & Booth, 2004).

Recent fMRI studies suggest that the rostrolateral PFC plays an important role in the representation of higher-order rules for switching between task sets. When people learn one pair of abstract conditional rules first (e.g., "if X, then A; if Y, then B") and then the opposite rules (e.g., "if X, then B; if Y, then A"), this region is strongly activated on trials involving the rule learned second (Bunge et al., 2003; Crone, Wendelken, et al., 2006). This and other findings suggest that participants represent the second rule as the opposite of the first rule and access the conditions of this second rule by referring to the first rule (Crone, Wendelken, et al., 2006). In other words, the rostrolateral PFC appears to represent a hierarchical rule structure that integrates two opposing rules.

A BRAIN-BASED ACCOUNT OF DEVELOPMENTAL CHANGES IN RULE USE

As we will show, the order of acquisition of various rule types corresponds to the order in which each of the implicated brain regions matures, with the orbitofrontal cortex maturing earliest and the dorsolateral and rostrolateral PFC maturing last. It is proposed that age-related improvements in children's rule use are made possible by increases in the hierarchical complexity of the rule sets that children can represent (Zelazo et al., 2003) and that the ability to represent hierarchical rule systems depends on the development of an increasingly complex hierarchical network of PFC regions.

Developmental Changes in the Prefrontal Cortex

Structural MRI has been employed to examine changes in brain structure over time within an individual (e.g., Gogtay et al., 2004). These longitudinal studies reveal complex developmental changes in the volume of cortical "gray matter," which reflects neuronal density and the number of connections between neurons (Giedd, 2004). Structural-MRI studies also reveal increases in cortical "white matter" across development, reflecting myelination (the formation of fatty sheaths around nerve fibers, which enables rapid neuronal communication), but the rate of change is steady throughout childhood and is similar across brain regions (Giedd, 2004). Longitudinal measurements of gray matter indicate that, within the PFC, the orbitofrontal cortex reaches adult levels earliest, followed by the ventrolateral PFC, and then by the dorsolateral PFC (Gogtay et al., 2004). A cross-sectional study focusing on the dorsolateral and rostrolateral PFC suggests that these regions exhibit similar, slow rates of structural change (O'Donnell, Noseworthy, Levine, & Dennis, 2005).

Compared to developmental changes in brain structure, much less is known about changes in brain function relevant to rule use. We have, however, conducted one developmental fMRI study focusing on flexible rule use (Crone, Donohue, Honomichl, Wendelken, & Bunge, 2006). Consistent with the account presented here, we observed greater activation in the lateral PFC for bivalent relative to univalent stimuli in children as young as 8 years old, although we have not yet tested younger children. Interestingly, we found age differences in the pattern of PFC activation across rule conditions between 8- to 12-year-olds, 13- to 17-year-olds, and young adults. In contrast, other parts of the brain showed mature patterns of rule-related activation earlier in development. Thus, improvements in rule use during middle childhood and adolescence (e.g., Zelazo et al., 2004) are likely related to maturation of the lateral PFC; whether this is also the case for improvements earlier in childhood remains to be seen.

Additionally, preliminary fMRI data from the Bunge laboratory are consistent with the prediction that the rostrolateral PFC matures late: Whereas 8- to 11-year-olds exhibit an immature pattern of activation in the rostrolateral PFC while performing a reasoning task, they show a mature pattern in more posterior prefrontal regions. It is important to note, however, that age differences in brain activation appear to be quite task specific, such that a particular region might be utilized in a similar way as in adults on one task, but may not yet be utilized to assist with another task.

IMPLICATIONS AND FUTURE DIRECTIONS

The correspondence between the development of rule use and the growth of the PFC lends support to the idea that age-related improvements in rule use (from using a single rule to switching between two rules to switching between two incompatible pairs of rules) depends on the ability to represent increasingly complex hierarchies of rules in which higher-order rules operate on lower-order rules by selecting among them. Between 3 and 5 years, for example, children show marked improvements in rule use that we propose may be understood in terms of the functions of the lateral PFC: using a set of bivalent rules while ignoring interference from incompatible rules (dorsolateral PFC), and representing task sets explicitly and selecting among them (rostrolateral PFC). According to this account, the hierarchical complexity of developing networks of PFC regions is reflected in the hierarchical complexity of the explicit rule systems that children are able to represent.

To properly test this hypothesis, additional research will be required. For example, it will be necessary to conduct longitudinal studies tracking within-subject changes in rule use, brain structure, and brain function from ages 2 to 18. Optical imaging techniques (which measure absorption of near-infrared light by the brain surface as a function of neural activity) lend themselves to this type of longitudinal design, as they involve noninvasive scalp recordings and have been used successfully in young children. Additional research will also be required to test our hypothesis concerning the role of rewards in rule use and its development. We have depicted the orbitofrontal cortex as representing lower-order rules than those represented by the lateral PFC (Fig. 1), but it is also possible that rule complexity and reward-related information are orthogonal aspects of prefrontal organization. That is, more anterior parts of the PFC may represent more complex rules, and more ventral parts of the PFC may represent value-related components of rules. In any event, however, the field of developmental cognitive neuroscience is now well positioned to learn much more about the neural bases of cognitive development, including the neural bases of rule use.

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