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Developmental Review 24 (2004) 133–153
DEVELOPMENTAL REVIEW
www.elsevier.com/locate/dr

Computational cognitive neuroscience of early memory development☆

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Received 28 August 2003

Abstract

Numerous brain areas work in concert to subserve memory, with distinct memory functions relying differentially on distinct brain areas. For example, semantic memory relies heavily on posterior cortical regions, episodic memory on hippocampal regions, and working memory on prefrontal cortical regions. This article reviews relevant findings from computational cognitive neuroscience on why different neural regions might be specialized for different types of memory, and how this might impact early memory development. These findings demonstrate computational trade-offs among different memory functions, such that a single system cannot specialize on more than one function. Instead, the anatomical and physiological specializations of posterior cortical, hippocampal, and prefrontal cortical regions support their associated functions. This computational framework provides a mechanistic way of understanding memory distinctions described at the conceptual level. The developmental relevance of this framework is discussed—in the context of specific models, where available—for category learning, infantile amnesia and developmental amnesics, and the development of flexible behavior.

Keywords: Computational trade-offs; Hippocampus; Prefrontal cortex; Semantic; Episodic; Working memory development

Different brain areas make distinct contributions to cognition. There is broad consensus on this view, although debates on the localization of function have had a long history. Arguments for localization of function have come from a broad range of

☆ Manuscript for special issue of *Developmental Review* on The Nature and Consequences of Very Early Memory Development, Mark Howe and Mary Courage (Eds.).

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0273-2297/$ - see front matter
doi:10.1016/j.dr.2003.09.008

perspectives, including phrenologists almost two centuries ago who felt bumps on the skull in an attempt to measure underlying brain areas, researchers over a century ago working with patients with brain damage, who noted that certain behaviors and abilities seemed to depend on specific regions of cortex, and current-day neuroimagers, who record images of differential brain activity in various tasks. In contrast, other researchers have argued that the brain works according to a principle of mass action, whereby all brain areas contribute to all functions, and the effects of brain damage depend on how much (rather than which part) of the brain is damaged (e.g., Lashley, 1929). Although these debates have been largely resolved in favor of some localization of function, with numerous specialized brain areas working in concert in the service of cognition and behavior, many related debates are still ongoing. For example, how much of the neural specialization that we see in the adult reflects modular systems versus highly interactive ones (e.g., Farah, 1994; Fodor, 1983)? How much of this specialization is innately specified versus learned through experience (e.g., Hermer & Spelke, 1996; Karmiloff-Smith, 1992)?

Nonetheless, converging evidence from patients with brain damage (e.g., Farah, 1990; Scoville & Milner, 1957; Stuss & Benson, 1984), neuroimaging studies (e.g., Braver et al., 1997; Eldridge, Knowlton, Furmanski, Bookheimer, & Engel, 2000; Thompson-Schill, Aguirre, & Farah, 1999), and single-cell recording data (e.g., Miller, Erickson, & Desimone, 1996; Tanaka, 1996) has led to fairly general agreement about three specializations for memory functions: posterior cortical regions for semantic memory (e.g., remembering what kind of an object a cup is, or the typical spatial arrangement of parts of a clock), hippocampal regions for episodic memory (e.g., remembering a conversation about email filing systems with certain friends in a Toronto subway), and prefrontal cortical regions for working memory (e.g., for mentally multiplying 42 times 17). This is not simply a one-to-one mapping, as other brain regions contribute to these memory functions, and other functions are subserved by these brain regions. However, these specializations appear to be important ones, which can be understood in a modeling framework in terms of computational trade-offs. Such trade-offs, and their developmental implications, are the focus of this review.

Computational framework for understanding neural specializations

A computational perspective can provide insight into how and why neural regions are specialized for different functions (reviewed in O'Reilly & Munakata, 2000). In particular, such specializations can be understood in terms of computational trade-offs, whereby two objectives cannot be achieved simultaneously. As a system specializes on its ability to achieve one objective, it must relinquish its ability to achieve another objective. For example, there is a computational trade-off between fast learning and slow learning; a system that specializes in learning rapidly is not well-suited to learning gradually and vice versa. Thus, if there are demands on a system for both fast and slow learning, these functions are likely to depend on distinct neural regions with unique specializations. Similarly, there is a computational trade-