THE COGNITIVE NEUROSCIENCES

Sixth Edition

David Poeppel, George R. Mangun,
and Michael S. Gazzaniga, *Editors-in-Chief*

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Introduction

SARAH-JAYNE BLAKEMORE AND
ULMAN LINDENBERGER

The present section of *The Cognitive Neurosciences* spans human behavioral and neural development from infancy to old age. This change to the section theme is welcome, as it signals that human development does not end with adolescence but continues into advanced old age.

Individuals organize their exchange with the physical and social environment through behavior. On the one hand, the changing brain and the changing physical and cultural environment shape behavioral development. On the other hand, behavior alters both the brain and the environment. Hence, environments and brains act not only as antecedents but also as consequences of moment-to-moment variability and long-term changes in patterns of behavior. The dynamics of this system give rise to the diversity of individuals' trajectories through life (Molenaar, 2012; Nesselroade, 1991).

The general goal of developmental cognitive neuroscience is to identify neural mechanisms that generate invariance and variability in behavioral repertoires from infancy to old age. By identifying the commonalities, differences, and interrelations in the ontogeny of sensation, motor control, cognition, affect, social processing, and motivation, both within and across individuals, the field can move toward providing more comprehensive theories of behavioral development across different periods of the lifespan.

In attempts to explain the age-related evolution of this system, *maturation* and *senescence* (i.e., aging-related decline) denote the operation of developmental brain mechanisms and their effects on changes in behavior, which are especially pronounced during early childhood and late adulthood, respectively. In addition, *learning*, at any point during ontogeny, denotes changes in brain states induced by behavior-environment interactions. Note, however, that maturation cannot take place without learning and that some forms of learning cannot take place without maturation. Similarly, the ways in which senescence takes its toll on the aging brain depend on an individual's past and present learning and maturational histories. To complicate matters even more, processes commonly associated with maturation are not confined to early ontogeny, and processes related to senescence are not restricted to old and very old age. For instance, neurogenesis and synaptogenesis, which qualify as maturational mechanisms promoting plasticity, continue to exist in the adult brain; conversely, declines in dopaminergic neuromodulation, which indicate senescence-related changes in brain chemistry, commence in early adulthood. Thus, maturation, senescence, and learning mutually enrich and constrain each other throughout the entire lifespan and should preferably be understood and studied as interacting forces constituting and driving the brain-behavior-environment system (Benasich & Ribary, 2018; Lindenberger, Li, & Backman, 2006).

Thus, developmental cognitive neuroscientists are faced with three challenging tasks. First, there is the need to integrate theoretical and empirical research across functional domains to attain a comprehensive picture of individual development. For instance, sensorimotor and cognitive functioning are more interdependent in early childhood (e.g., Diamond, 2000) and old age (e.g., Lindenberger, Marsiske, & Baltes, 2000) than during middle portions of the lifespan, and developmental changes in either domain are better understood if studied in conjunction.

Second, there is a need to understand the mechanisms that link short-term variations to long-term change. Short-term variations are often reversible and transient, whereas long-term changes are often cumulative, progressive, and permanent. Establishing links between short-term variations and long-term changes is of eminent heuristic value, as it helps to identify mechanisms that drive development in different directions.

Third, to arrive at mechanistic explanations of behavioral change requires the integration of behavioral and neural levels of analysis. At any given point in the lifespan, one-to-one mappings between brain states and behavioral states are the exception rather than the rule, as the brain generally offers more than one implementation of an adaptive behavioral outcome. Therefore, ontogenetic changes in behavioral repertoires are accompanied by continuous changes in multiple brain-behavior mappings. Some of these remapping gradients may be relatively universal and age-graded, whereas others may be more variable, reflecting genetic differences, person-specific learning histories, the path-dependent nature of developmental dynamics, or a combination of all three. The resulting picture underscores the diversity and malleability of the organization of the brain and behavior as well as the constraints on diversity and malleability brought about by (1) universal age-related mechanisms associated with maturation and senescence, (2) general laws of neural and behavioral organization, and (3) cultural-social as well as physical regularities of the environment.

Research on brain development in the second half of the 20th century focused almost entirely on nonhuman animals and revealed a great deal about early neuronal and synaptic development (Wiesel & Hubel, 1965). These advances in animal research followed pioneering research in developmental psychology, particularly by Vygotsky and Piaget (Chapman, 1988). Their studies, which involved observing and analyzing children's behavior in meticulous detail, changed contemporary thinking about children's minds. Today, theory-guided series of behavioral experiments strongly support the claim that the foundational capacities of very young children are organized by guiding principles in physical, psychological, and sociomoral core domains. In this vein, Buyukozer Dawkins, Ting, Stavans, and Baillargeon propose in the opening chapter to this section that early sociomoral reasoning is guided by the principles of fairness, harm avoidance, in-group support, and authority.

While developmental psychology made great progress in the last century, it remained relatively removed from developmental neuroscience. Research on human neural development was heavily constrained by the technical challenges of studying the living human brain and, until fairly recently, was limited to the study of postmortem brains. In the past decades, however, the field of developmental cognitive neuroscience has undergone unprecedented expansion, at least in part due to technological advances. In particular, the increased and concerted use of various MRI techniques in children has created new opportunities to track structural and functional changes in the developing human brain. The use of these imaging methods has propelled our knowledge of how the human brain develops, and the data from developmental imaging studies have in turn spurred new interest in the changing structure and functions of the brain over the entire lifespan. Fifty years ago, who would have imagined that scientists would eventually be able to look inside the brains of living humans of all ages and track changes in brain structure and function from intrauterine development into old age?

Age-graded changes in the structure of the human brain from childhood to early adulthood are addressed in the chapter by Tamnes and Mills. They focus on measurements of brain morphometry and measurements derived from diffusion tensor imaging (DTI) while also discussing novel measures and approaches to examine structural brain development. Whereas structural MRI has enriched our knowledge of age-related changes in regional volume and structural connectivity, functional magnetic resonance imaging (fMRI), in concert with electroencephalography (EEG) and near-infrared spectroscopy (NIRS), has revealed developmental changes in regional brain activity and functional connectivity. Today many labs around the world use fMRI to investigate how neural systems associated with particular cognitive processes change with age. Crone and van Duijvenvoorde report the neural correlates of cognitive and affective decision-making in school-aged children, adolescents, and adults. They show that the development of basic to complex levels of cognitive control follows a pattern of specialization with age in the prefrontal cortex and the posterior parietal cortex, such that these areas are more strongly and more selectively recruited for specific tasks. Kilford and Blakemore trace the development of the social brain in adolescence and provide rich evidence for the substantial and protracted development of multiple aspects of social cognition, as well as the structural and functional development of the social brain network, during this period of life.

Inquiries into the plasticity of the brain and behavior are a rich source of developmental information; by assessing "changes in change," they offer the promise to observe the operation and proximal consequences of developmental mechanisms. Taking a lifespan and phylogenetic perspective, Walhovd and Lövdén review the evidence for age-graded differences in human plasticity from infancy to old age. This sets the stage for the chapter by Raz, who takes a systemic look at senescent changes in the brain and behavior, with particular emphasis on the role of vascular and metabolic factors. The aging brain is notorious for detrimental changes, but some older adults appear to display brain maintenance, defined as a widespread lack of senescent brain changes and age-related brain pathology. Nyberg and Lindenberger focus on the structural and functional maintenance of the hippocampus and argue that it is the primary determinant of preserved episodic-memory functioning in old age. Finally, Mather directs our attention to the role of the locus coeruleus norepinephrine system and provides evidence that the integrity of this system is crucial for maintaining cognitive functions in old age.

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