92 The Significance of Cognitive Neuroscience: Findings, Applications, and Challenges

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The field of cognitive neuroscience has been lauded for its potential to integrate disparate domains such as neurobiology and philosophy, and to provide new insights into human behavior. Although initially cognitive neuroscience was seen as perhaps no more than the intersection between neuropsychology and cognitive science, it has since become an independent area of inquiry, with a membership easily rivaling those of its parent disciplines. Given its origin as a multidisciplinary science, it should come as little surprise that the current state of the field is best characterized by expansion into areas of research that were formerly considered off-limits to neuroscientific study. For instance, since the early 2000s, topics such as emotion, decision making, and social cognition have risen to prominence both in terms of the number of papers published and also in terms of the number of pages they occupy in the current edition of this book. This latest edition also includes a new section on "neuroscience and society," reflecting the increasing role of cognitive neuroscience research in informing social policy.

However, the story of cognitive neuroscience's success isn't solely one of increasing breadth, but also one of rapid adoption of new methods and technologies. As is evident from the preceding chapters, these advances have paved the way for significant progress in our understanding of the human brain and human behavior. In this chapter, we chart the advances that the field has made in recent years. Some of these advances have been theoretical in nature, reflecting recent paradigm shifts in how we view the roles of individual brain regions and large-scale brain networks. Other advances have been primarily methodological: for instance, the five editions of this book have borne witness to the rapid development of functional imaging methods, spurred on by enormous advances in technology. For example, developments in both scanner technology and computational power have allowed for the collection of finer resolution data at a much faster rate. Early neuroimaging studies typically acquired slices as large as seven millimeters (Buckner et al., 1996; Tootell et al., 1995). In contrast, current functional MRI (fMRI) scanners are capable of collecting scans that are only one millimeter thick, and whole-brain coverage is typically achieved in about two seconds. The increasing size and complexity of modern-day data sets has been paralleled by increases in computational power, allowing scientists to develop new methods to store, catalog, and mine large data sets for new discoveries, leading to entirely new fields of study such as neuroinformatics (see chapter 83 by Marcus, this volume). New research initiatives such as the Human Connectome Project (www.humanconnectomeproject.org), which are amassing an enormous collection of neuroimaging data, are already capitalizing on these resources. Of course, these technological changes carry their own theoretical impact; for instance, increasing emphasis on neuroimaging has led to new efforts to understand neural function and dysfunction by studying the active, behaving brain.

Today, cognitive neuroscience should be viewed not only as a field with great potential, but also of great achievements. Here we highlight many of these achievements, as well as our vision of the future of cognitive neuroscience.

Applications of cognitive neuroscience

An important achievement of cognitive neuroscience today is its capacity to translate basic research results into the realm of clinical research and intervention. Indeed, the balance of cognitive neuroscience studies has recently shifted toward an increase in clinical research, sometimes at the expense of research on foundational questions in basic neuroscience. While the health implications of neuroscience research should inform and often guide research questions, this should not preclude the pursuit of basic research. To best lay the foundation for future discoveries of clinical importance within cognitive neuroscience research, it is imperative that basic research be encouraged and funded.

Examples of the societal impact of cognitive neuroscience research follow; all are grounded in basic research. Studies of individual differences, from the level of the gene to the level of brain connectivity, are increasingly informing truly personalized medication and treatment choices. The brain, once thought to be immutable after development, is now known to be alterable through behavioral training. While these findings are exciting, it is critical to ensure that they are clearly presented to a broad audience in order to produce the greatest benefit to society. In particular, education practices and policies could be strengthened by such research findings.

INDIVIDUAL DIFFERENCES Traditional cognitive neuroscience imaging studies focus on mean group analysis of physiological fluctuations across samples, the results of which are assumed to generalize to wider populations. However, this approach may provide uninformative results, neglecting salient aspects of large interindividual variants relevant to identifying cognitive brain networks. Evidence for the vital impact of interindividual differences can be seen in imaging studies on motor behavior and decision making that link variations in anatomical brain connections to behavioral and cognitive outcomes (Kanai & Rees, 2011). These studies show promise in illuminating the contribution of interindividual variants on brain circuitry and plasticity.

However, tracking the time course of structural plasticity in interindividual imaging studies is a primary issue (Kanai & Rees, 2011). Network science (NS), the study of complex networks and topologies using mathematics, offers tools to track structural plasticity. More specifically, NS economy of brain networks traces wiring and rewiring on various time scales, allowing measurements of plasticity to be linked to fluctuations in cognitive states (Bullmore & Sporns, 2012). Merging NS techniques with studies of interindividual variation will advance brain network research in cognitive neuroscience and could lead to the development of imaging-based metrics to assist in clinical treatment of cognitive disorders.

COGNITIVE INTERVENTION, REHABILITATION, AND OPTIMIZATION Better insight into individual differences in structural and functional brain characteristics, individual differences in genetic makeup, and the relation of these differences to behavioral variation may open new opportunities for personalized approaches in cognitive neuroscience applications, as can be seen in the following examples. In psychiatry, individual differences in gene expression can influence responses to psychoactive drugs, mediated by differences in brain metabolism and neural networks (Costa & Silva, 2012; Gvozdic, Brandl, Taylor, & Muller, 2012). Characterization of a brain injury patient's affected and nonaffected brain networks using imaging methods can help guide treatment selections, optimizing neurological rehabilitation (Ham & Sharp, 2012). In the context of training, individual white matter integrity within the corpus callosum predicts training response in aging adults (Wolf et al., 2012), while hippocampal structural characteristics and functional connectivity partly predict response to mathematics tutoring in school-age children (Supekar et al., 2013). More detailed genotyping and phenotyping of individuals before administration of pharmacological and nonpharmacological interventions can improve health care, much as knowledge of individual characteristics can inform therapeutic decisions about customized intervention strategies. Such knowledge will not only improve individual health care outcomes, but may also improve clinical research, for example via targeted patient selection for clinical trials.

Reorganization and optimization of neural networks can be achieved through physical exercise (i.e., experience-dependent neural plasticity) and cognitive training (i.e., learning; experience-dependent cognitive plasticity). Structural, functional, and chemical plasticity accompany behavioral changes following training, including in neurogenesis and synaptogenesis; promotion of neurotrophic activity and neurotransmitter efficiency; recovery of function; and reduced cognitive decline and psychiatric symptoms (Barbour, Edenfield, & Blumenthal, 2007; Dresler et al., 2013; Will, Galani, Kelche, & Rosenzweig, 2004). Improved performance and neural activation during cognitive tasks have been suggested to occur by engagement of previously underactive brain systems or compensation from other neural regions (Kelly, Foxe, & Garavan, 2006). Based on these findings, we propose that exercise increases neural efficiency and facilitates the neural context for learning. Therefore, combining exercise and cognitive training within a study may produce a synergistic effect with lasting neurocognitive outcomes.

Technological advancement may provide novel training opportunities. The use of video games for "brain training" has recently become popular, captivating the public interest. Some findings have suggested that these training programs do not lead to generalized benefits in a normal adult population (Owen et al., 2010), while others show promise in promoting maintenance of information (Jaeggi, Buschkuehl, Jonides, & Shah, 2011), sustained attention (Dye, Green, & Bavelier, 2009), executive control (Strobach, Frensch, & Schubert, 2012), reasoning (Strenziok et al., 2013), and in remediating symptoms in patients and other special populations (Vinogradov, Fisher, & de Villers-Sidani, 2012). Future work will show whether evidence-based game development aimed at improving cognition could provide insight for incorporating neurocognitive training into our daily lives. Biofeedback and neurofeedback technologies may be the future in optimizing training by providing real-time feedback on performance and psychological/physiological state (e.g., attention, arousal, stress). Additionally, transcranial direct current stimulation and transcranial magnetic stimulation hold promise in modulating cognition. These tools may be used to enhance cognition in healthy aging (Dresler et al., 2013) and to achieve functional recovery in impaired states such as addiction (Sokhadze, Cannon, & Trudeau, 2008) and psychiatric disorders (Mizenberg & Carter, 2012). Moreover, transcranial direct current stimulation, transcranial magnetic stimulation, and other technologies may act as elements of neuroprosthetic systems for locomotion, environmental control, or communication in cases of neural insult or congenital conditions (Lehembre et al., 2012; Nicolas-Alonso & Gomez-Gil, 2012). Finally, they may facilitate collaboration in a multiuser environment (Pope & Stevens, 2012). Therefore, these technologies can be used as adjunctive interventions in illness and can boost cognitive performance in healthy individuals or groups.

NEUROSCIENCE AND EDUCATION One primary role of neuroscience is to inform education practices through advocacy and community outreach. Research on marginalized populations, such as those with financial disadvantages or mental illnesses, has revealed the negative impact of inadequate or ineffective education and its downstream consequences. As the intricacies of cognitive development are uncovered, we find that a better understanding of brain systems is fundamental in supporting both pedagogical theory and practice. Neural systems display degrees of plasticity that vary throughout development, and this knowledge can be used to target at-risk groups with neural training programs (Neville et al., 2013). Institutions such as the Economic and Social Research Council and the Society for Neuroscience recognize that we are now equipped to provide better training for teachers by bolstering their understanding of research on learning, memory, attention, and social behavior (e.g., Blakemore & Choudhury, 2006; Evans, Saffran, & Robe-Torres, 2009; Stevens, Sanders, & Neville, 2006). Teachers who are informed by such research may, in turn, promote more adaptive curricula fashioned to address the strengths and weaknesses of students from various environments and genetic backgrounds.

Theoretical neuroscience

MAPPING BRAIN TO COGNITION Twenty-five years ago, cognitive neuroscience was conceptualized as the scientific study of the neural substrates of cognition. Its initial research program was envisioned in terms of finding the brain mechanisms responsible for the production of cognitive processes and functions. However, as the field has developed, the research objectives have evolved. The astonishing technical and methodological advances that have taken place in the last 10 years have revealed that the mapping of cognitive functions onto brain mechanisms is substantially more complicated than originally thought. On the one hand, the same neural mechanisms appear to be implicated in a number of ostensibly distinct cognitive functions; on the other hand, these same cognitive processes appear to be supported by the interactions amongst numerous, seemingly disparate brain areas. As a result, the field of cognitive neuroscience is moving toward a more complex understanding of the neural substrates of cognition, one that does not assume simplistic one-to-one mapping between any single brain region and a specific cognitive domain.

An example of this theoretical transition comes from recent work studying the hippocampus, a brain structure that has traditionally been considered to be critically and selectively involved in conscious, episodic, autobiographical memory. However, emerging neuroimaging, neurophysiological, and neuropsychological evidence demonstrates that the hippocampus is also involved in a range of other processes, including simulating possible future events and counterfactual thinking (Schacter et al., 2012), discriminating complex visuospatial stimuli (Lee et al., 2012), and learning and retrieving associative relationships without conscious awareness (Hannula & Greene, 2012). A similar story can be told about many other brain regions. Indeed, the engagement of a particular brain region during apparently distinct psychological functions seems to be the norm rather than the exception, suggesting that brain function cannot easily be classified by psychological taxonomy (Anderson, 2010).

Mapping Brain Networks Just as it has become clear that no individual brain region performs a single cognitive function, a wealth of recent work also suggests that cognition is supported by the dynamics of large-scale networks of brain regions. This shift in perspective has been facilitated largely by the widespread adoption of studies using functional connectivity MRI (fc-MRI) to characterize the spontaneous activity of the brain at rest in the absence of an explicit experimental task. Spontaneous activity is believed to reflect not only anatomical constraints but also Hebbian sculpting by co-activation (Lewis et al., 2009); thus, resting-state fc-MRI provides a window into statistical histories of functional coupling. Therefore, a brain region's resting functional connectivity profile can inform questions about cognition and provide additional correlates of behavioral or physiological measures. Although much still remains to be learned about how resting-state functional connectivity relates to cognition, studies thus far have yielded promising insights.

The growing use of resting-state fMRI (and other measures of connectivity) in cognitive neuroscience reflects a broader trend across many scientific disciplines to approach data sets from the perspective of NS. The human brain is a network with several levels of organization, so an NS approach is relevant to most neuroscientists, regardless of whether they study cognition at the scale of microcircuits or large-scale brain systems. At the large-scale level, efforts are underway to describe the domain-general functional organization of the cortex, cerebellum, and subcortical tissues, and to relate this organization to patterns of co-activation seen within and across particular cognitive domains. These initial efforts have resulted in coarse maps of human brain organization (Power et al., 2011; Yeo et al., 2011) that reflect and inform decades of functional neuroimaging. Studies of specific nodes in functional networks have begun to identify properties that correlate with cognitive abilities such as intelligence (Cole, Yarkoni, Repovs, Anticevic, & Braver, 2012).

At the microcircuit level, interactions among small clusters of neurons has revealed mechanistic principles of neural computation, which seem to be ubiquitous throughout the brain and powerful enough to implement complex features of neural machinery. Interneurons can configure networks with different properties, depending on whether they exert inhibitory or excitatory connections within their local circuits (Lee et al., 2012; Wang, 2002). The study of network properties and dynamics at much finer scales will become more common in the near future as the dissemination and refinement of techniques for controlling and quantifying neural activity with fine temporal and spatial scales improves (e.g., via optogenetics and the CLARITY process; see Chung & Deisseroth, 2013, etc.).

Mapping Networks Across Time Recent advances have also elucidated some of the mechanisms by which neural and cognitive processes emerge and develop across time. Developmental cognitive neuroscience is important because it can help us understand individual differences, inform educational practices, and pave the way for tailoring remediation techniques for atypically developing children. However, until recently, most neuroscientific accounts have disappointed developmental theorists by relegating developmental processes to brain maturation. The maturational or "predetermined epigenesist" approach to development cannot account for the complex and dynamic ("probabilistic") interactions that happen within and between all levels of organization across time, from genes to the external environment (Gottlieb, 1992). Nor can they account for the dynamics of change in genetic and environmentally induced disorders, nor answer questions such as whether an early, basic-level deficit might be followed by compensation or compounding of effects. Take, for example, the dyadic interaction between a child and her mother. If the mother were told that her child had a neurodevelopmental disorder (e.g., autism), would the mother interact with her child differently? If yes, then the child's responses would reflexively change. Indeed, Karmiloff-Smith and colleagues (2012) have observed that some parents find it difficult to allow their atypically developing child to freely roam about and learn from their environment as a typically developing child would. This may result in a less richly explored environment, which in turn would constrain brain, motor, and sociocognitive development.

Individual differences in mother-child interactions are known to constrain cognitive development even in the case of typical development (Karmiloff-Smith et al., 2010, 2012), raising questions not contemplated in the past. As a consequence of such empirical findings, researchers are abandoning the idea that brain and cognitive development are yoked to some predetermined maturational process. Old, static questions regarding the "age" at which a certain "brain module" comes online, where the modules are located, and which modules are "impaired" or "intact" are giving way to new, dynamic questions concerning the emergence of and changes in neural circuits and cognitive functions over developmental time, which domains interact across developmental trajectories, and which aspects of our dynamic environments interact with and alter ontogenesis.

Challenges and conclusion

The cognitive neurosciences have progressed markedly since the last edition of this volume (Aminoff et al., 2009). Borne along in part by advancing new and refined methodologies, our understanding of the relationship between brain and behavior has advanced considerably. This progress paves the way for future breakthroughs, but also presents new challenges. Here, we mention a few noteworthy developments and the advances that they may foreshadow, as well as some potential pitfalls the field may face as it continues to develop.

New Directions in Cognitive Neuroscience The chapters included in this book delineate the current state of the cognitive neurosciences, and hint at the headway that may be gained in the future. Recent findings in neuroimaging have shown that it is possible to decode a person's conscious experience based only on his or her brain activity (Horikawa, Tamaki, Miyawaki, & Kamitani, 2013; Nishimoto et al., 2011). This ability to detect the presence of certain cognitive states, during both wake and sleep, may enable reconstruction of dreams and have interesting implications, such as legal implications for lie detection.

Some of the latest developments in brain-machine interface (BMI) technologies enable the restoration of body mobility in individuals suffering from motor deficits (e.g., paraplegics; Lebedev & Nicolelis, 2011; Nirenberg & Pandarinath, 2012; Wang et al., 2013) and the restoration to near-normal vision in the blind (Nirenberg & Pandarinath, 2012). Integration of cognitive neuroscience and engineering may enable whole-body BMI and sensory substitutions (Reich, Maidenbaum, & Amedi, 2012), improving quality of life across many domains.

Recent developments on olfaction research—including theoretical models positing geometrical relationship among odorants (Haddad, Lapid, Harel, & Sobel, 2008)—have revealed connections between odor molecules and their corresponding neural and perceptual responses. Such theories may allow us to determine what sensation a given odorant will have on our olfactory systems or to sense odorants outside the range of normal human sensation, laying the foundation for the development of an electronic nose that could detect diseases (Wilson & Baietto, 2011), allowing for "photographing" an odor (e.g., for categorization, reconstruction, or later comparison), and enabling the reconstruction of odor experience through BMI (e.g., for those with anosmia). The cognitive neuroscience of odor-space research is still relatively nascent (e.g., as compared with vision neuroscience), so it is reasonable to expect great continuing advances in this area in the years to come.

Previously, progress in areas such as developmental and clinical cognitive neurosciences was slow, because well-established techniques in healthy adult research (e.g., fMRI) are often unsuitable for research with difficult-to-test infants or children and clinical populations. Research in children and special populations (e.g., patients with sensory processing disorder, schizophrenia, fragile X) is now possible with the introduction of new, lightweight, comfortable, and quickly and easily positioned functional near-infrared spectroscopy (which measures the hemodynamic response to cortical neural activation; see, e.g., Lloyd-Fox, Blasi, & Elwell, 2010); quick-application electroencephalographic "hairnets" and high-impedance electroencephalographic systems; and head-mounted and fixation-responsive eye trackers. These powerful new tools (and numerous others) can reveal how neural and cognitive processes become specialized over developmental time, recover from insult, or respond to medical intervention, having considerable implications for basic research as well as health care and education.

The recent development of optogenetic tools for precise online control of neural activity (see chapter 82 by Zalocusky and Deisseroth, this volume) has already begun to deliver substantial insight, providing causal evidence for theories of learning (Steinberg et al., 2013) and memory (Ramirez et al., 2013). This technique offers great promise to advance our understanding of neuronal signaling as well as to provide better treatment in the clinic (for example, supplanting beneficial but imprecise deep-brain stimulation in Parkinson's patients, and enhancing the viability of BMI prostheses for patients with brain injury or amputated limbs).

From Science to Society A deluge of media coverage has accompanied the headway made in the cognitive neurosciences, highlighting the challenge of how to best disseminate neuroscience knowledge. There remains a large gap between the empirical evidence and the public perception in both our understanding of the brain and our applications of that knowledge (Eagleman, 2013; Racine, Waldman, Rosenberg, & Illes, 2010). For example, the concept of "brain training" has recently experienced an increase in both popularity and criticism (Cook, 2013), and despite a paucity of data supporting the idea that improvements in cognitive-training tasks can transfer to a quantitative increase in general intelligence (e.g., Owen et al., 2010), companies implying as much have proved to be incredibly popular. However, evidence is building that some types of training can enhance durable and transferable cognitive performance in several domains (see, e.g., Jaeggi et al., 2011; Strenziok et al., 2013), drawing attention to the need for further research and the fact that greater efforts must be made to clearly communicate both the promise and the limitations of neuroscience research.

This issue extends well beyond the popular press and has nontrivial implications. In criminal law, similar uncertainty exists between what neuroscience *can* tell us and what neuroscience is *expected* to tell us. There is a growing appreciation of research that questions the validity of eyewitness testimonies (Schacter & Loftus, 2013; see the section XI introduction by Sinnott-Armstrong and Roskies, this volume) and that highlights the neural substrates of the "criminal mind" (e.g., Farisco & Petrini, 2012; see chapter 89 by Gaudet, Anderson, and Kiehl, this volume). Notably, recent advances in fMRI and optogenetics have respectively led to claims of "mindreading" (Stahl, 2009) and "total recall" (Hornyak, 2013) from the media, when in fact the utility of such methods to the legal system remains limited for the foreseeable future. Moving forward, the field must continue to encourage public dissemination of neuroscience research without overstating the implications of our work (Eagleman, 2013; Racine et al., 2010).

Just as new technologies have changed the way that scientists acquire, store, and share data, they have also offered new means for scientists to develop studies and communicate their findings with each other and with the general public. For example, blogs and tools like Twitter allow scientists to rapidly respond to new findings and papers in a form of post-publication peer review, and growing support for study preregistration (Chambers & Munafo, 2013) may enhance the collaborative basis and quality of studies during their formation. As academic journals have moved almost entirely into the online sector, the barriers to disseminating new findings are diminishing, and there is increasing emphasis on establishing new mechanisms for rapid, open-access publishing (Kriegeskorte, Walther, & Deca, 2012). Although these developments affect the scientific community as a whole, given the widespread public interest in the brain sciences, it behooves cognitive neuroscientists to embrace technologies that will enable us to share our knowledge with the general public.

The proliferation of literature and methods (as illustrated by the breadth of the preceding chapters) exposes another challenge for the future of the field. With maturation, cognitive neuroscience risks the fractionation of its subdisciplines into independent fields, diluting its interdisciplinary strengths. Emerging technologies that facilitate the interpretation of these vast literatures (e.g., Yarkoni et al., 2011) and their data will be of increasing importance as the field progresses.

We look forward to the developments over the next five years, and expect the next edition of this volume will be as rich with progress and promise for the future of cognitive neuroscience as this one.

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