Cognitive neuroscience

PRZEMYSLAW TOMALSKI

Introduction

How cognitive activity is organized at the neural level has been the subject of scientific study for more than a century, but the discipline of cognitive neuroscience has emerged only in the last few decades. Cognitive neuroscience is concerned with functional brain organization that supports the breadth of human cognitive processes: sensory perception, execution of complex movements, representation of the external world, language and social communication, mathematical abilities, abstract reasoning, and many more.

Naturally, the majority of research has been focused on the adult brain, demonstrating that certain areas of the cerebral cortex are specialized to process different kinds of information (e.g., parts of the temporal cortex specialize in the processing of information about faces: age, gender, identity, etc.). As a result, many authors considered the human brain to possess a rather fixed organization where cortical areas can be mapped onto distinct modules of cognitive activity (e.g., visuospatial module, social module, or language module). However, this static view has been difficult to reconcile with many strands of developmental research, especially on children with developmental disorders or those who suffered traumatic brain injury early in life (Karmiloff-Smith, 1998). Consequently, a different view came to the fore that functional brain organization emerges gradually throughout many years of life and is to a large extent dependent on interactions with the environment. This meant that there is no strict uniform blueprint of development that all human brains follow in every detail.

Undoubtedly, most human brains follow the same overall course of development, which is determined in part by genetic factors. Also, for the majority of infants and children, the nervous system follows a typical trajectory of development, as a result of similar early experience. In contrast, children who experience early sensory deprivation or have a congenital condition may process the same stimuli (e.g., faces, human voice, or touch) very differently. This is because their brains have followed an atypical pathway of development and may have specialized in different categories of stimuli than typically developing brains.

This entry starts with an explanation of why cognitive neuroscience relies on many different methods to arrive at converging evidence. Subsequent sections outline the three most important theoretical approaches to the functional development of the brain: The maturational perspective, the skill-learning perspective, and interactive specialization. Each approach is illustrated by recent research on the development of brain structure and function. In conclusion, there is a brief look at the most important limitations of the cognitive neuroscience approach to development with some indications of future research directions in this field.

Converging-methods approach

Progress in researching the development of functional brain organization has been achieved thanks to the availability of many different methods for studying brain structure and function (Posner, 2002). What makes cognitive neuroscience a unique scientific enterprise is the frequent use of different sources of information that complement each other. This converging-methods approach relies on studies of both non-human animals and humans using behavioral tests and methods for monitoring various kinds of neural activity. These methods encompass the monitoring of response properties of single nerve cells, changes in electrical and metabolic activity of entire brain regions, and imaging of changes in brain structure and connectivity between regions through to methods of stimulating or inhibiting brain activity. Historically, data on the difficulties of patients with localized brain damage and complementary data from animals with similar lesions were also vital sources of information. Cognitive neuroscientists skillfully combine these sources of information to generate hypotheses about the causes and timing of changes in brain structure and function that lead to changes in observable cognitive behavior.

Perspectives on functional brain development

Different theoretical perspectives have been proposed to explain the relationship between the activity of certain brain areas and cognitive activity. The following section outlines three approaches identified by Johnson (2001) that have gained most empirical evidence: (1) the maturational perspective, (2) the skill-learning perspective, and (3) the interactive specialization perspective. They are not necessarily mutually exclusive but often generate different predictions with respect to empirical findings.

Maturational perspective

According to this view, the biological determinants of brain development are the key factors in the emerging cognitive abilities observed during child development. Thus, the maturation of specific brain regions leads to changes in the way certain behavior is being performed or certain stimuli are processed. For example, improvements in sensory processing in infancy are thought to be the result of increasing myelination of relevant sensory areas. Myelin sheath surrounds nerve fibers, which significantly increases the speed of neural transmission. In most areas, fibers are gradually myelinated from the second half of the prenatal period through to the end of the second year of life. This process continues for the next decade or so in a few areas with more protracted development, such as the anterior part of the frontal lobe. Many authors have observed that maturational changes in myelination of pathways that transmit auditory information to the cortex are very well reflected in developmental changes of brain responses to sounds. As a result, electrical responses recorded from the scalp surface of the immature newborn brain are very different from those found in adults. The maturation of pathways transmitting auditory information throughout infancy would lead to infant brain responses becoming gradually more adult-like (Csibra, Kushnerenko, & Grossmann, 2008). In other words, the age-related changes in brain activity correspond with those in the pattern of myelination and connectivity between brain regions.

Despite the successes of the maturational approach, it has failed to explain how postnatal experience shapes the emerging brain connectivity and functional specialization. This is illustrated by studies that compared individual differences in structural brain development (e.g., growth of individual areas) with improvements in specific skills in childhood (e.g., memory or response inhibition). Although differences in the volume of gray matter in the frontal lobe are associated with performance in a memory task in children (Sowell, Delis, Stiles, & Jernigan, 2001), it remains unclear what exactly is driving this association between brain structure and function. Crucially, it is a subject of a debate whether such associations of individual differences in brain structure and cognitive skill are related to differences in prior experience. This question is the prime focus of the next perspective.

Skill-learning perspective

While the maturational perspective underscores the importance of biological brain development for changes in cognitive functioning, the skill-learning approach emphasizes the influence of practice of a skill on improvements in the neural structures that support this skill. One idea stemming from this approach is that similar changes at the neural level will accompany the acquisition of the skill in infants and adults alike. This is evident in the case of perceptual as well as motor learning.

In the case of specialization of areas that support visual recognition, Gauthier, Skudlarski, Gore, and Anderson (2000) have provided evidence that extensive training in discrimination of artificial objects (known as 'greebles') will result in responses of a region of the temporal lobe typically thought to be uniquely specialized for recognizing human faces (fusiform face area; see Plate 11). Further studies have shown that in expert birdwatchers or car specialists, the seemingly face-specific fusiform area can be equally active following long-term visual experience with that class of objects (Bukach, Gauthier, & Tarr, 2006; but see Robbins & McKone, 2007). Some parallels with infant face recognition exist. In the first months of life, infants distinguish between individual monkey faces and human faces equally well. However, most human infants have disproportionately more experience with faces of their own species, so by the age of 9 months, they are more likely to become experts in human, not monkey faces. However, exposure to monkey faces between 6 and 9 months of age allows infants to discriminate monkey faces at 9 months, an ability that is otherwise lost at that age (Pascalis *et al.*, 2005). These studies provide evidence for the notion that experience of one's environment is vital for functional brain development.

What follows from the skill-learning hypothesis is that atypical sensory or motor experience will

https://doi.org/10.1017/9781316216491.092

cause some cortical areas to specialize in different skills from the same areas in individuals with typical experience. This is illustrated by cases where congenital alterations of early motor experience (e.g., malformations of upper limbs following prenatal exposure to thalidomide) affect the representation of body parts in the primary motor cortex. Individuals with congenitally compromised hand function due to malformations caused by prenatal exposure to toxins become experts in foot use for various daily activities that are performed by hands in typical development. A functional neuroimaging study by Stoeckel, Seitz, and Buetefisch (2009) showed that in these individuals, parts of the primary motor cortex which typically represent hands actually represent their feet. This is highly surprising, because the organization of cortical representations of different body parts was considered to be strongly genetically determined. Their study shows that even basic neural representations of body parts can be altered by atypical experience from the prenatal period onwards.

Motor learning in adults can lead to similar remapping of the primary motor cortex, albeit on a less spectacular scale. Studies with adult humans and macaque monkeys revealed similar effects of learning motor sequences of finger movements across several weeks (see Ungerleider, Doyon, & Karni, 2002). In such cases, the motor representation involved in task performance expands at a cost of contraction of neighboring representations that were not activated during the motor task.

Extensive training, however, does not always restore function in the case of congenital sensory deprivation. Even after having their hearing restored by cochlear implant, congenitally deaf infants do not develop typical speech processing abilities despite extensive and prolonged rehabilitation (Kral & Eggermont, 2007). Similar results were obtained for some face-processing skills in children who experienced early visual deprivation due to congenital cataracts that were removed some months after birth (Le Grand, Mondloch, Maurer, & Brent, 2001). These findings suggest that the age of acquisition of a skill is crucial for functional brain organization of that skill, and that with age some areas of the cortex have a decreased capacity for specialization. In other words, there are sensitive periods in the development of cortex, and typical development of neural responses may depend on the provision of specific kinds of stimulation at a certain age.

Interactive specialization perspective

While the maturational perspective is focused on the onset of activity in different brain regions and the skill-learning perspective emphasizes the role of experience, the next approach highlights the critical importance of development in the organization of connections between regions. A growing number of neuroimaging studies of human cognition suggest that cognitive abilities in children and adults alike are not supported by activity in single areas but by networks of subcortical and cortical areas.

Bressler and Menon (2010) have put forward the idea that functional brain organization should be analyzed in terms of large-scale brain networks, which are systems of areas that are distributed across the entire extent of the brain. Two kinds of networks can be identified: task-related and resting state. The former are active when the brain is engaged in specific kinds of cognitive activity, such as face recognition, mental arithmetic, or speech comprehension. The resting-state networks are more active when we are awake but not engaged in a particular activity, and they are considered an intrinsic feature of a healthy brain. Disturbances in the activity of resting-state networks are observed in many neurological disorders and psychiatric conditions, as well as in children born preterm or those with developmental disorders.

One feature of large-scale networks is their ongoing synchronization, which can be measured as high levels of oscillatory activity in electrical potentials recorded from the scalp surface. This framework might help us to understand why in some developmental disorders, such as autism and Williams syndrome, individuals might differ significantly from each other and why they may show difficulties across many cognitive domains. For example, reduced synchronization of visual areas in autism is related to abnormalities in different aspects of visual perception such as the binding of different visual features of objects into one entity (Grice *et al.*, 2001).

How do functional brain networks emerge in development? The interactive specialization framework proposed by Johnson (2001) explains how changes in connections between regions are related to the acquisition of a new ability. This approach assumes that the response properties of a specific region are partly determined by its pattern of connectivity to other regions, as well as its own patterns of activity. Some cortical regions may begin with poorly defined functions, and consequently they are partially activated in a wide range of different contexts and tasks. Activity-dependent interactions between regions hone the functions of regions such that their activity becomes restricted to a narrower set of stimuli or processes.

In the development of face perception, interactive specialization predicts increases in the degree of localization of face-sensitive responses as well as the level of specialization in parts of visual cortex, such as the fusiform face area or the inferior temporal gyrus. These predictions are consistent with recent

https://doi.org/10.1017/9781316216491.092

neuroimaging data showing gradual emergence of the cortical network supporting face perception (see Plate 11). Several studies have measured the pattern of responses in the visual cortex that are specific to faces, everyday objects, or images of houses in younger children, adolescents, and young adults. Starting with a large number of widely distributed areas and a low level of face selectivity in young children, there is a shift toward a more distinct set of smaller and more selective cortical areas in older children and adults (Scherf, Behrmann, Humphreys, & Luna, 2007).

This approach can be fruitful in explaining the neural mechanisms of some developmental difficulties in, for example, reading. Inappropriate or insufficient connectivity between regions may lead to disturbances of brain functions that support reading abilities, resulting in the emergence of developmental dyslexia. In this case, neuroimaging studies of brain activity and of structural connections between regions indicate that the development of reading relies on the functional integration of distributed brain regions (see Richlan, 2014). Difficulties in reading, such as in developmental dyslexia, are related to reduced connections between language-related areas in the temporal, frontal, and parietal regions of the brain cortex. On the other hand, in skilled readers, the activity of the relevant brain networks appears to be very well segregated from the networks supporting other skills and from resting-state networks.

Limitations of cognitive neuroscience applied to the study of development

Developmental cognitive neuroscientists have so far made remarkable progress in explaining the consequences of functional brain development for dramatic changes in the cognitive skills of infants, toddlers, and children. However, the achievements of the past few decades have also revealed several important limitations of this approach.

First, the widespread use of neuroimaging techniques has led in some cases to a shift away from theories that propose cognitive mechanisms in favor of generating theories purely at the neural level of explanation (Coltheart, 2006). For example, it used to be widely accepted that "more brain tissue is better" for cognitive functioning. In many cases, children with more rapid brain growth, or a greater increase in the volume of certain brain areas, show better developmental outcomes, an example being that greater volume of the left inferior frontal gyrus is associated with better language outcomes (Raizada, Richards, Meltzoff, & Kuhl, 2008). However, recent studies suggest that some developmental disorders (e.g., autism) are associated with greater head circumference and brain volume (see Johnson, Gliga, Jones, & Charman, 2015). Thus, simple notions drawn from brain morphology may prove misleading when trying to understand the associations between brain structure and function.

Second, for a long time experimental neurocognitive research has been accused of studying human cognition in isolation from the human environment. For example, the vast majority of research has been conducted with small samples of children from well-educated, middle-class families living in developed countries. Meanwhile, studies where participants represented the full range of family socioeconomic status (SES) showed large disparities in task performance that were related to SES (see Hackman, Farah, & Meaney, 2010 for review). This example shows that in order to understand the complexity of human development, cognitive neuroscientists need to move beyond small-scale experimental studies and on to large-scale longitudinal studies spanning many decades of human life and capturing multiple environmental and genetic factors.

Conclusions

The integration of behavioral and neuroimaging work in studies of different populations has led to a great expansion of our understanding of the neural bases of cognitive abilities. Developmental cognitive neuroscientists have achieved this progress thanks to advances in methods for studying the developing brain in combination with converging data from behavioral assessments, animal research, and computer modeling. Overall, three theoretical approaches to the development of functional brain organization were discussed: the maturational, skill-learning, and interactive specialization perspectives. Together these different approaches have helped to complete a picture of the trajectories of typical brain and cognitive development. These accounts differ in their approach to the question of how the biological determinants of brain development can be modified at different stages by experience and environmental factors.

Cognitive neuroscience is a highly dynamic field of study, with important changes in research paradigm occurring quite frequently. While it is difficult to map future directions of research, some attractive trends are emerging. One is the concerted effort to map developmental changes of brain connectivity. Large initiatives for brain research in the United States and Europe have prioritized the task of mapping inter-regional connections and modeling how the resulting networks enable the computations necessary for a range of cognitive abilities. One example is the Developing Human Connectome Project (www.developingconnectome.org), which is an initiative to map and visualize all growing connections from the early stages of prenatal brain development through to the early postnatal period. A particular challenge is to conduct a series of scans of pregnant women throughout the last term of pregnancy to obtain detailed images of the brain structure of individual growing fetuses. Such complete maps of changing connections can then be compared between infants born on time and preterm or those with genetic risk of developmental disorders in order to identify the most vulnerable brain networks.

Another promising line of research concerns the increase in our understanding of variation between individuals in functional brain organization. To date, the majority of research has focused on describing universal developmental processes, while relatively little attention has been devoted to explaining the neural basis of differences between individuals. Increasingly more work needs to be carried out to explain the complex interplay of genetic and environmental factors and their influences on emerging brain networks throughout prenatal and postnatal development. This enterprise may clarify the causes of variation in cognitive abilities. For instance, it may show biological bases of inter-individual differences in reading or movement coordination. It would also significantly further our understanding of pathways in brain development that lead to developmental disabilities and disorders.

See also

Learning theories; Fetal and neonatal magnetoencephalography; Fetal ultrasonography; Magnetic resonance imaging (MRI); Functional near-infrared spectroscopy; Longitudinal and cross-sectional designs; Connectionist modeling; Prenatal sensory development; Cognitive development during infancy; Executive functions; Face perception and recognition; Multisensory development; Sleep and cognitive development; Reading and writing; Perception and action; Brain and behavioral development; Educational neuroscience; Social neuroscience; Classification of developmental disorders and diseases; Autism; Dyslexia; Prematurity and low birthweight; Williams syndrome; Connectomics; Behavioral genetics; Developmental genetics; Systems neuroscience; Future of development is degenerate, pluripotent and multi-scaled

Further reading

Andersen, S.L., & Pine, D.S. (Eds.) (2014). *The neurobiology of childhood*. Heidelberg, Germany: Springer.

Fahrbach, S.E. (2013). *Developmental neuroscience:. A concise introduction*. Princeton, NJ: Princeton University Press.

Johnson, M.H., & de Haan, M. (2015). *Developmental cognitive neuroscience: An introduction* (4th ed.). Oxford, UK: Wiley-Blackwell.

Nelson, C.A., & Luciana, M. (2008). *Handbook of developmental cognitive neuroscience* (2nd ed.). Cambridge, MA: MIT Press.

Stiles, J. (2008). *Fundamentals of brain development: Integrating nature and nurture.* Cambridge, MA: Harvard University Press.

References

Bressler, S.L., & Menon, V. (2010). Large-scale brain networks in cognition: Emerging methods and principles. *Trends in Cognitive Sciences*, 14, 277–290.

Bukach, C.M., Gauthier, I., & Tarr, M.J. (2006). Beyond faces and modularity: The power of an expertise framework. *Trends in Cognitive Sciences*, 10, 159–166.

Coltheart, M. (2006). What has functional neuroimaging told us about the mind (so far)? *Cortex*, 42, 323–331.

Csibra, G., Kushnerenko, E., & Grossmann, T. (2008). Electrophysiological methods in studying infant cognitive development. In C.A. Nelson & M. Luciana (Eds.), *Handbook of developmental cognitive neuroscience* (2nd ed., pp. 247–262). Cambridge, MA: MIT Press.

Gauthier, I., Skudlarski, P., Gore, J.C., & Anderson, A.W. (2000). Expertise for cars and birds recruits brain areas involved in face recognition. *Nature Neuroscience*, 3, 191–197.

Grice, S.J., Spratling, M.W., Karmiloff-Smith, A., Halit, H., Csibra, G., de Haan, M., & Johnson, M.H. (2001). Disordered visual processing and oscillatory brain activity in autism and Williams syndrome. *Neuroreport*, 12, 2697–2700.

Hackman, D.A., Farah, M.J., & Meaney, M.J. (2010). Socioeconomic status and the brain: Mechanistic insights from human and animal research. *Nature Reviews: Neuroscience*, 11, 651–659.

Johnson, M.H. (2001). Functional brain development in humans. *Nature Reviews Neuroscience*, 2, 475–483.

Johnson, M.H., Gliga, T., Jones, E., & Charman, T. (2015). Annual research review: Infant development, autism, and ADHD – Early pathways to emerging disorders. *Journal of Child Psychology and Psychiatry*, 56, 228–247.

Karmiloff-Smith, A. (1998). Development itself is the key to understanding developmental disorders. *Trends in Cognitive Sciences*, 2, 389–398.

https://doi.org/10.1017/9781316216491.092

Kral, A., & Eggermont, J.J. (2007). What's to lose and what's to learn: Development under auditory deprivation, cochlear implants and limits of cortical plasticity. *Brain Research Review*, 56, 259–269.

Le Grand, R., Mondloch, C.J., Maurer, D., & Brent, H.P. (2001). Early visual experience and face processing. *Nature*, 410, 890.

Pascalis, O., Scott, L.S., Kelly, D.J., Shannon, R.W., Nicholson, E., Coleman, M., & Nelson, C. (2005). Plasticity of face processing in infancy. *Proceedings of the National Academy of Sciences*, 102, 5297–5300.

Posner, M.I. (2002). Convergence of psychological and biological development. *Developmental Psychobiology*, 40, 339–343.

Raizada, R.D.S., Richards, T.L., Meltzoff, A., & Kuhl, P.K. (2008). Socioeconomic status predicts hemispheric specialisation of the left inferior frontal gyrus in young children. *NeuroImage*, 40, 1392–1401.

Richlan, F. (2014). Functional neuroanatomy of developmental dyslexia: The role of orthographic depth. *Frontiers in Human Neuroscience*, 8, 347.

Robbins, R., & McKone, E. (2007). No face-like processing for objects-of-expertise in three behavioural tasks. *Cognition*, 103, 34–79.

Scherf, K.S., Behrmann, M., Humphreys, K., & Luna, B. (2007). Visual category-selectivity for faces, places and objects emerges along different developmental trajectories. *Developmental Science*, 10, F15–F30.

Sowell, E.R., Delis, D., Stiles, J., & Jernigan, T.L. (2001). Improved memory functioning and frontal lobe maturation between childhood and adolescence: A structural MRI study. *Journal of the International Neuropsychological Society*, 7, 312–322.

Stoeckel, M.C., Seitz, R.J., & Buetefisch, C.M. (2009). Congenitally altered motor experience alters somatotopic organization of human primary motor cortex. *Proceedings of the National Academy of Sciences of the United States of America*, 106, 2395–2400.

Ungerleider, L.G., Doyon, J., & Karni, A. (2002). Imaging brain plasticity during motor skill learning. *Neurobiology of Learning and Memory*, 78, 553–564.