ARTICLE

Developing human brain functions

Mark H. Johnson, winner of the Society's Presidents' Award 2008, describes the emerging field of developmental cognitive neuroscience

Developmental cognitive neuroscience has recently emerged as a new interdisciplinary field that seeks to understand how the physical development of the brain relates to the huge changes in cognitive and psychological abilities that we witness from newborn to adolescent. Advances in child-friendly methods have allowed us to directly investigate how regions of the brain become increasingly fine-tuned for specialised functions. These methods have also helped reveal that postnatal brain development is a dynamic, plastic process in which many emerging functions are shaped by the physical and social environment of the developing child. Indeed, the child helps to further her own subsequent brain development by actively seeking out novel and important types of information from her environment.

questions

Research suggests that the young infant's brain is, to some extent, maleable. Should we pursue research into early enrichment programmes? Should we restrict this to those at risk for genetic and/or environmental reasons?

resources

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From birth to the teenage years the human brain undergoes around a four-fold increase in its total volume. Accompanying this huge increase in brain size are equally dramatic changes in the motor, perceptual and cognitive abilities of infants and children. In terms of their traditional scientific disciplines, the latter phenomena have been the domain of developmental psychologists, while the former were firmly in the realm of the neuroscientist. For decades these fields were pursued in parallel, but largely isolated from each other.

Indeed, for developmental psychologists to refer to neuroscience evidence was sometimes frowned upon because such data were deemed to be misleading or distracting from the core issues of interest. When neuroscience evidence was referred to by developmental psychologists it was commonly from the perspective that a particular developmental change in behaviour was 'maturational' – that is, not attributable to learning, and therefore not requiring a psychological level explanation. However, over the last decade or two a number of changes have contributed to the emergence of a new subfield in which scientists are specifically interested in relating developmental changes in perception, cognition and behaviour in the developing child to the underlying growth of the brain. This new field has now become known as 'developmental cognitive neuroscience' (Johnson, 2005).

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Measuring event-related potentials

What factors have contributed to the emergence of this new field of developmental cognitive neuroscience (henceforth DCN)? First, and not to be underestimated, is the development of methods that allow us to study human brain structure and function during ontogeny. Some of these methods involve the imaging of brain function in non-invasive ways that are very safe and friendly to infants and their parents. For example, when groups of neurons within the brain fire in synchrony the tiny electrical changes they emit can be measured by passive sponge sensors resting on the scalp (electroencephalography – EEG or event-related potentials – ERP) (Johnson et al. 2001). In another method, tiny changes in the patterns of absorption of low-level light beams can be used to assess changes in the amount of oxygenated (or deoxygenated) blood to particular regions of the brain when they are active (a method called near infrared spectroscopy – NIRS) (Meek, 2002). These methods promise to revolutionise our understanding of functional brain development in humans.

A second factor contributing to the emergence of DCN has been increasing evidence for the plasticity of the brain, particularly during ontogeny. Far from

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being the unfolding of a rigid genetic plan, much current evidence shows that postnatal human brain development involves a two-way interaction between brain structure and emerging functions (Johnson, 2005). In other words, the postnatal structural and functional development of the brain is influenced by the environment in which it is raised. This is particularly so for humans since our postnatal brain development is considerably slowed down even relative to our most closely related primate cousins. The environment that helps shape our brains involves not only the physical world of objects, surfaces, gravity, and so on, but also the social world of other human beings. Further, the influence of the environment on the brain includes not only aspects of the social and physical world that are specific to individuals (such as being exposed to spoken English), but also aspects that are common to most members of our species (such as being exposed to a language of some kind). This suggests that some of the common aspects of brain structure and function in humans could arise not only because we have genes in common, but also because we share a common environment (with gravity, solid objects, the presence of other humans, etc.).

In addition to new methods for baby-friendly brain imaging, we have new theoretical tools for relating changes in the neuroanatomy of the brain to the psychological and computational functions it subserves. The rise of a class of brain-inspired psychological models, sometimes called 'connectionism' or neural network models (Elman et al., 1996), formalises how changes in networks of neurons and their connections bring about changes in computation and behaviour (connectionist or neural network modelling). The purpose of these computer models is not just to simulate changes in cognition and behaviour during development, but also to generate testable predictions for future research (Mareschal et al., 2007).

Even though DCN is a relatively young discipline, a number of themes of discovery are emerging. Prior to the advent of DCN, developmental psychology was rife with debate between nativists, who argued for the importance of genetic specification of core principles that structure cognition (Spelke at al., 1992), and empiricists who emphasised the role of learning and experience. While pockets of evidence from DCN can be selected to support either of these views, the majority of scientists in this new field are struck by the evidence that human functional brain development is a constructive process in which the state of the brain at one (earlier) stage helps it to select the appropriate experience necessary for advancing to the next (later) stage. In other words, human postnatal brain development is what is termed a self-organising process (Mareschal et al., 2007).

For example, much evidence shows that babies and young children are most interested in new events and stimuli – things that they don't yet understand. By spending time looking at a new object or event, they are exposing their brains to a new source of information that, in turn, will contribute further to their own brain development. Some readers may detect that this constructivist perspective resembles in at least a general way the views of Jean Piaget, one of the founders of developmental psychology. While Piaget did not have any of the powerful theoretical tools or methods at our disposal today, it is interesting to speculate on how he would view current research in the field.

Courtesy of Michael Crabtree Portraits

Near infrared spectroscopy in action

Perhaps the clearest example of babies seeking out the aspects of the environment necessary for their own subsequent brain development comes from the attention and effort they devote to interacting with other humans, and particularly their primary caregivers. From birth, human newborns orient toward and respond to faces, particularly to a smiling face with direct (mutual) gaze (Farroni et al., 2002). This newborn bias ensures that, from birth, babies engage other human beings in social interaction. Studies using ERP and NIRS methods have shown that at a few months of age babies' processing of other people's faces is deeper and more detailed when accompanied by the cues associated with communicative interaction, such as direct gaze (Grossman et al. 2008). Furthermore, objects that are presented or gazed at by adults tend to be subsequently processed more deeply, and recognised better, by young babies. Thus, human babies are biased to seek out information necessary for their own subsequent brain development from adult humans. And, of course, parents are predisposed to provide this information for their offspring in a variety of ways.

Another theme from recent work in DCN is that of the emerging specialisation of functions within the human brain. Contrary to the popular view that postnatal brain development involves 'switching on the lights' in particular regions of the brain at different ages, functional brain-imaging studies are showing us that nearly all parts of the brain begin life responsive to sensory stimuli, but that some regions are poorly tuned (Johnson, 2001). That is, these regions begin life capable of being activated under a wide variety of different circumstances and with a range of different sensory stimuli. During development these responses become more specifically tuned to particular task contexts or sensory stimuli. This is because the regions become sculpted to support increasingly specific computations. For example, regions that are selectively tuned to faces in adults show a much broader response

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profile in young children in that the regions in question respond equally well to other visual objects. With age, the face-selectivity of the region increases even to the extent of selectivity depending on the particular tasks related to face perception (e.g. individual recognition vs. expression recognition vs. eye gaze direction detection) (Cohen-Kadosh & Johnson, 2007). Thus, at least for the overlying cerebral cortex, much of human postnatal development can be characterised as the gradual emergence of increasingly specific functions within regions of the brain.

A specific part of the cortex that has been associated with higher cognitive functions such as inhibition, working memory and planning is the prefrontal cortex – the region of the brain that lies behind our forehead. The textbook view is that this region is silent over the first year of life, and that it becomes functional in stages beginning at around 12 months. Recent work in DCN suggests that while the functions that the prefrontal cortex supports clearly get more advanced as childhood proceeds, the region is active from at least the first few months after birth (Johnson, 2005). This poses something of a paradox. Why is it that the prefrontal cortex is active from early in life, yet the aspects of cognition associated with the region in adults emerge only slowly during childhood?

One answer to this question may be the important role that the prefrontal cortex plays in the acquisition of new skills. Functional imaging of adults while they acquire complex new perceptual or motor skills shows that this region is activated during the early stages of learning the new skill. Once the skill has been acquired, however, the involvement of the region decreases, or even disappears, and other parts of brain take over. The newborn infant has to acquire a vast range of skills that seem mundane to us as adults. For example, learning to use vision and proprioceptive feedback to successfully reach for and grasp an object takes several months of failed attempts and near misses. Such seemingly simple tasks to adults may be as challenging to the infant brain as learning to drive is for an adult. The hypothesis that the prefrontal cortex is important for the acquisition of basic motor and perceptual skills in infants is currently being investigated by researchers in DCN.

Another theme of discovery in DCN concerns the pathways of progression in development, sometimes called 'developmental trajectories'. Research here is comparing typically developing infants and children with those with developmental disorder like Williams syndrome, fragile-X and autism. In some cases, close comparison of these syndromes is revealing that developmental trajectories can diverge in initially subtle ways, but that this deviation becomes compounded later on by increasingly atypical interactions with the social and physical environment as development proceeds. For example, a baby at-risk for autism may begin with slightly atypical patterns of social interaction with their caregivers that then become compounded with development as they elicit slightly atypical responses from others. In other cases, infants and children at risk may recover and re-join the typical developmental trajectory at a later point in development.

The human child's ability to learn from others is unparalleled

"seemingly simple tasks to adults may be as challenging to the infant brain as learning to drive"

What of the future? DCN is clearly a young discipline and, like a toddler, much work remains to be done to bring together the fragments of knowledge that we have acquired so far into a coherent overall picture. Nevertheless, of all the cognitive and neurosciences DCN is probably the field with the most scope for practical and clinical application. First, as mentioned above, in DCN investigators often study atypical or at-risk babies and children alongside typically developing ones. Understanding the brain basis of developmental disorders such as autism gives us insights both into the immediate causes of cognitive and behavioural disturbance, and into the developmental causes of the full profile of symptoms. For example, some recent studies raise the possibility that measures of brain function may provide an earlier warning sign of a later diagnosis of autism than behavioural symptoms (Zwaigenbaum et al., 2005).

Another avenue of application for DCN is education. While educational packages based on folk neuroscience myths are quite popular in some schools, there still remains a big gulf between basic neuroscience and classroom practice. Recent interest in 'educational neuroscience' suggests that this gulf will be bridged in the near future (Szucs & Goswami, 2007).

Turning to pre-schoolers, there are a variety of populations of infants who are at risk for either genetic or environmental reasons. For example, children raised in low socio-economic status homes tend to be at risk for a variety of adverse mental health and mental ability outcomes. An important societal agenda for the future will be to see whether we can identify babies most at risk and deliver targeted and theoretically motivated environmental enrichment programmes.

A final area of application is for industrial developments in artificial intelligence and robotics. Despite the areas in which present-day computers outsmart humans, the human child's remarkable ability to learn from others remains unparalleled. Thus, studying how the human brain acquires expertise and knowledge over a lifetime may provide important insights for those trying to develop a more natural artificial intelligence.

These potential areas of application, when taken along with its basic science interest, suggest a healthy future for developmental cognitive neuroscience.

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