

FUNCTIONAL BRAIN DEVELOPMENT IN HUMANS

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There is a continuing debate in developmental neuroscience about the importance of activity-dependent processes. The relatively delayed rate of development of the human brain, compared with that of other mammals, might make it more susceptible to the influence of postnatal experience. The human infant is well adapted to capitalize on this opportunity through primitive biases to attend to relevant stimuli in its environment. The infant's interaction with its environment helps to sculpt inter- and intraregional connections within the cortex, eventually resulting in the highly specialized adult brain.

From birth to teenage years, there is a fourfold increase in the volume of the human brain. During this period, there are also marked improvements in motor, cognitive and perceptual abilities. Although both of these aspects of human development have been studied for several decades, it is only recently that investigators have turned their attention to how they relate to one another.

In other words, how does the physical growth of the brain relate to the emergence of new behavioural abilities during infancy and childhood? Addressing this question is not just of academic interest, but could have profound implications for clinical, educational and social policies¹. As adults, we have brains that are highly structurally and functionally specialized; for example, discrete regions of our cerebral cortex support components of cognitive functions such as language and face processing. Although much of cognitive neuroscience and neuropsychology is concerned with dissociating and identifying the functions of these regions in adults, the question of how such specializations arise in the first place has received less attention. One perspective is that the functional specialization of regions of the cerebral cortex arises through intrinsic genetic and molecular mechanisms, and that experience merely has a role in the final 'fine tuning'. An alternative view is that some aspects of human functional brain development involve a prolonged process of specialization that is shaped by postnatal experience.

A parallel debate to that among developmental neuroscientists rages among developmental psychologists. Some developmental psychologists argue that the human infant is born with 'innate modules' and 'core knowledge' relevant to the physical and social world. Others propose that many of the changes in behaviour observed during infancy are the result of general mechanisms of learning and plasticity.

In this article, I summarize research on the postnatal neuroanatomical development of the human brain, and findings on perceptual and cognitive development during infancy. I go on to outline three approaches to understanding the relationship between the two: functional brain development. The focus is on the first two years of life, as this is when the most pronounced advances in brain structure and behaviour occur.

Human postnatal neuroanatomical development closely follows the sequence of events observed in other primates, albeit on a slower timescale. A model of the evolution of the brain that successfully predicts the timing of different neural developmental events in various mammalian species² has recently been extended to human prenatal development³. The model predicts that the more delayed the general time course of development in a species, the larger the relative volume of the later developing structures (such as the cerebral cortex, and particularly the frontal cortex). In accordance with this general prediction, the slowed rate

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Box 1 | Getting answers from babies

Conducting behavioural experiments with young babies who cannot yet speak or make manual responses poses a challenge. However, by using the ability that babies have from birth to move their eyes to scan the visual world, and by tapping into their spontaneous interest in novel events, several different paradigms have been developed. One such technique is called 'habituation'. It involves showing an infant the same, or related, pictures or sequences repeatedly. At initial presentations, infants spend a long time looking at the stimulus, but after several more exposures they glance only briefly at them. At this point the baby is 'bored' with the original image, and the experimenter presents a new one. If the infant categorizes the new display as being different, she will return to her original, prolonged looking time. On the other hand, if she cannot perceive any difference, or if she regards the test display as being of the same category as the training one, there will be no recovery of looking time. In another procedure, preferential looking, an infant is simply presented with two alternative pictures and the time spent looking at each is computed. Measuring these differences in looking time can tell us about what infants know. Other methods that have proved to be successful rely on changes in the baby's sucking rate or changes in heart rate. These kinds of experiment have taught us that during the first year, babies come to know that objects are solid, that they continue to exist even when out of sight, and that they will fall downwards from table tops.

of development in humans is associated with a relatively larger volume of cortex and an especially large frontal cortex. But the relatively delayed time course of human brain development has another important benefit. It allows a prolonged postnatal period during which interaction with the environment can contribute to the tuning and shaping of the brain's circuitry.

There are several ways to study postnatal neuro-anatomical development in humans. Post mortem analyses have been conducted, but usually with small sample sizes. Developmental **positron emission tomography** (PET) and **magnetic resonance imaging** (MRI) studies are becoming more common, but are usually restricted to infants with suspected clinical symptoms⁴⁻⁶. Data obtained using these methods have now converged sufficiently to allow several conclusions to be drawn. By around the time of birth in humans, most neurons have migrated to their appropriate locations within the cortex, hippocampus, cerebellum and other regions. However, some neurogenesis continues into adulthood in the hippocampus⁷ and possibly in other structures⁸. Subcortical structures can be clearly delineated and resemble their adult forms. Although some of the chief landmarks (sulci and gyri) of the cerebral cortex are visible at birth, it remains relatively immature in terms of its inter- and intraregional connectivity. The increase in the volume of the brain from birth to teenage years is not uniform: there is differential growth between subcortical and cortical regions, and between different regions of cortex. For example, whereas there is a rapid increase in synaptogenesis around the time of birth for all cortical areas studied, the most rapid burst of synapse formation and the peak density of synapses occur at different ages in different areas⁹⁻¹¹. In the visual cortex, there is a rapid burst of synapse formation between 3 and 4 months, and the maximum density — about 150% of the adult level — is reached between 4 and 12 months. Synaptogenesis starts at the same time in the prefrontal cortex, but the density of synapses increases much more slowly and does not reach its peak until well after the first year¹⁰.

The differential time course of development of different cortical regions can also be observed in the living human brain by PET imaging¹². In infants under 5 weeks of age, glucose uptake is highest in sensorimotor cortex, thalamus, brainstem and the cerebellar vermis, whereas by 3 months of age, there are considerable rises in activity in the parietal, temporal and occipital cortices, basal ganglia and cerebellar cortex. Maturation rises are not found in the frontal and dorsolateral occipital cortex until approximately 6–8 months of age. An adult-like distribution of resting activity within and across brain regions is observed by the end of the first year¹². These measures, like the measures of synapse density, also show an increase above adult levels. There is a continuing rise in overall resting brain metabolism (glucose uptake) after the first year of life, with a peak — about 150% of adult levels — at around 4–5 years of age for some cortical areas.

As with other species, regressive events are commonly observed during human brain development. For example, in the primary visual cortex the mean density of synapses per neuron starts to decrease at the end of the first year¹³. In humans, all cortical regions studied are subject to this rise and fall in synaptic density, which declines to adult levels during later childhood. The postnatal rise-and-fall developmental sequence can also be seen in other measures of brain physiology and anatomy. For example, PET studies show that although the overall level of glucose uptake reaches a peak during early childhood that is much higher than that observed in adults, the rates return to adult levels after about 9 years of age. The extent to which these changes relate to those in synaptic density is being investigated further.

In addition to the formation of dendritic trees and their associated synapses, most fibres become myelinated during postnatal development. Owing to the increased lipid content of the brain caused by this myelination, structural MRI images can provide a clear grey-white matter contrast, which allows quantitative volume measurements to be made during development. Although there is some controversy about the interpretation of images from infants under 6 months (due to the relatively high water content of both grey and white matter at this age), the consensus is that brain structures have the overall appearance of those in the adult by 2 years of age, and that all the main fibre tracts can be observed by 3 years of age^{14,15}. In some reports, it is suggested that after a rapid increase in grey matter volume up to approximately 4 years of age, there is then a prolonged period of slight decline that extends into adult years (REF 16, but see REF 14). Whether this decline is due to dendritic and synaptic pruning remains unknown, although in some studies the time courses of the rise and fall coincide¹⁴. Changes in the extent of white matter are of interest because they are presumed to reflect inter-regional communication in the developing brain. Although increases in white matter continue through adolescence into adulthood, particularly in frontal brain regions¹⁷, the most rapid changes occur during the first 2 years. Myelination seems to begin at birth in the pons

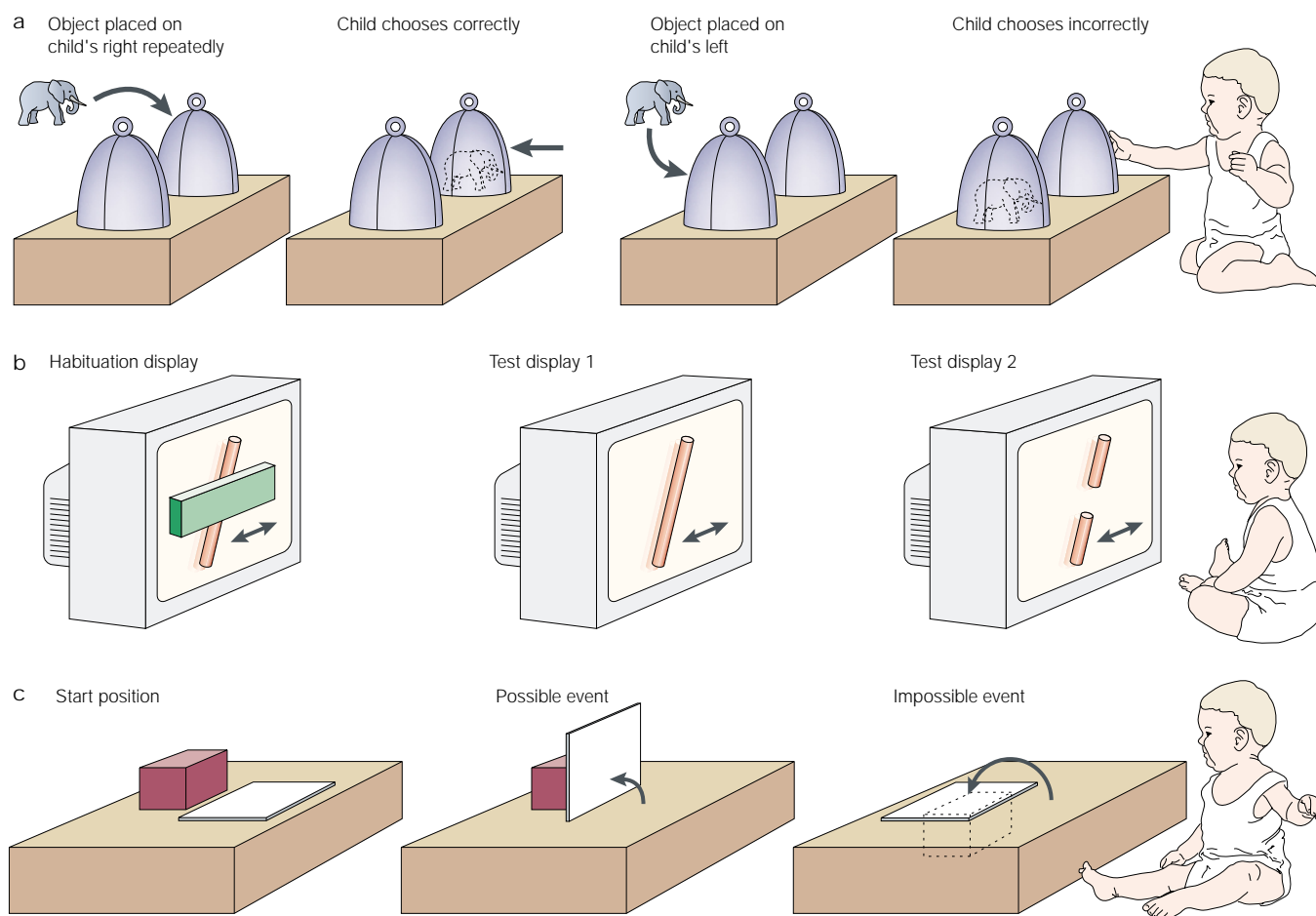


Figure 1 | Behavioural testing in infants. a | An object retrieval task that infants fail up to 9 months of age. In full view of the infant, the experimenter hides the object in one location and the infant reaches for it successfully. After a few such trials, the experimenter hides the object in a second place but the infant searches again at the original location⁴⁹. **b** | A visual habituation technique can be used to show that infants from as young as 4 months perceive the left-hand figure as a continuous rod moving behind an occluder. Infants dishabituated (found novel) the test display with two short rods, indicating that they perceptually 'filled in' the occluded area in the habituation display. Infants under 4 months are only partially successful in such tasks, depending on the complexity of the display⁷⁵. **c** | The infant views two event sequences, one possible and one impossible, in which a flap is rotated towards a solid cube. In the 'possible' case the flap stops when it comes into contact with the object. In the 'impossible' case the flap rotates through the object. Infants as young as 4 months appear surprised (look longer) when viewing the impossible event, showing that they appreciate that objects are solid and (usually) non-compressible⁷⁶.

 Animated online

and cerebellar peduncles, and by 3 months has extended to the optic radiation and splenium of the corpus callosum. At around 8–12 months of age, the white matter associated with the frontal, parietal and occipital lobes becomes apparent¹⁵.

Cognitive and perceptual development in infants
Considerable knowledge about the cognitive and perceptual abilities of human infants has accumulated as a result of behavioural testing (BOX 1). Although much has been discovered about the early development of motor, visual, attentional and language skills, in this selective review the focus is on the visual processing of two domains of paramount importance to the developing infant: inanimate (non-social) objects, and animate (social) objects such as human beings.

A major challenge to the developing perceptual system is to segment parts of the visual input into separate objects. In natural scenes, object information is often

ambiguous, underspecified and continually changing. The perceptual system must develop the ability to define object boundaries, fill in missing information and bind together different features to compose whole unitary objects. Various experiments have sought to establish the extent of these abilities at birth, and the extent to which they are derived from experience of complex visual scenes. It is clear that even newborns have some structure to their perceptual representations, but the point at which children effortlessly perceive objects as independent bounded entities in the way that adults do is the subject of debate^{18,19}, especially because there are several compelling examples of failures of babies in what are (to adults) simple tasks. For example, until 9 months of age, infants will often fail to reach for a desirable object when it is hidden or occluded (out of sight is out of mind), fail to detect that an object has changed while passing behind an occluding surface, and not be surprised when two dissimilar independent

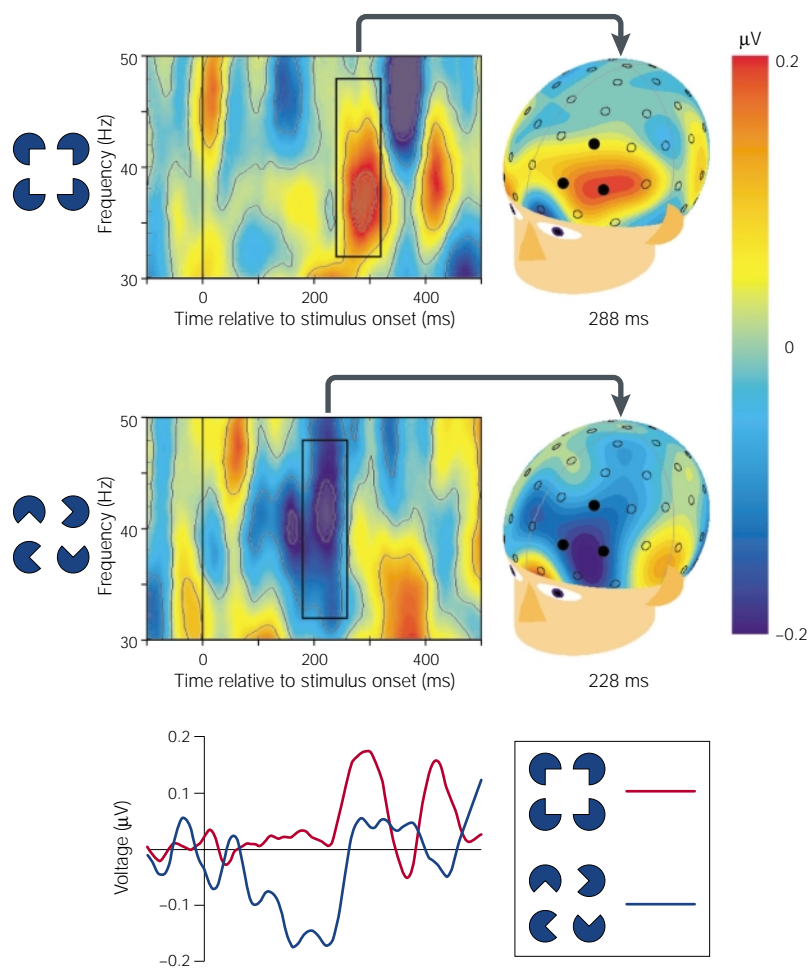


Figure 2 | Gamma-band EEG responses from infants show evidence of perceptual binding from at least 8 months. Time–frequency plots show the same characteristic gamma (40–Hz) ‘burst’ at around 280 ms after stimulus onset as is observed in adults. This burst is evident with stimuli such as illusory figures in which spatially separate features are integrated to compose a unitary object. Concordant with behavioural data with illusory objects, gamma bursts are not observed in 6-month-old infants. Adapted with permission from REF. 28 © 2000 American Association for the Advancement of Science.

objects suddenly start to move as if they are one (FIG. 1a). These failures are particularly striking when compared with infants’ successes in other object processing tasks. For example, 4-month-old infants perceive two ends of a moving rod to continue behind a surface that occludes the middle, and expect objects to be solid and not compressible (FIG. 1b, c).

Focusing more on the success of infants in these paradigms, one influential view is that, from early in life, we have core knowledge about the basic properties of objects²⁰. According to this hypothesis, babies are able to perceive unitary objects in scenes on the basis of innate ‘principles’ such as those of solidity and spatio-temporal continuity. Experiments using behavioural HABITUATION (BOX 1) have provided evidence that infants of 4 months and older are sensitive to these principles in some testing paradigms. Although it is tempting to interpret such evidence in terms of precocious ‘adult-like’ abilities in infants, there are several reasons for caution. First, even 4 months of life represent hundreds of hours

of potentially relevant visual experience, and some neural network computational models capable of learning aspects of object properties very rapidly show similar patterns of successes and failures in simulated versions of infant test paradigms^{21,22}. Second, when babies younger than 4 months are tested in studies similar to those described above, they fail unless several different perceptual cues are presented^{23,24}. Third, infants rely more on spatial and temporal information, and less on object-specific feature information, than do adults in many object processing tasks^{25–27}. And finally, recent studies show changes in the neural basis of object processing during the first year of life²⁸ (FIG. 2). Although the newborn human brain is clearly biased to process objects in certain ways, and to learn rapidly about their properties, it is not until the second year of postnatal life that children seem to perceive and process objects in the way we do as adults.

In addition to inanimate (non-social) objects, the visual world of the baby is also inhabited by animate (social) objects, such as fellow human beings. Perceiving and acting on information from caregiver adults is clearly critical for the survival and development of babies. The obvious importance of social information processing, and the evidence for specialization of the adult brain for language and face processing, has led some to speculate that there are pre-specified modules within the infant brain to process socially relevant information^{29–31}. An extreme alternative view is that as infants are raised in an intensely social environment, experience-sensitive neural circuits are moulded by this early experience, and so indirectly give rise to a ‘social brain’. However, as with the processing of inanimate objects, there is now an emerging consensus centred on the middle-ground, namely that infants are born with biases to attend to and process certain stimuli differently, and that these biases shape subsequent learning and plasticity. For example, numerous studies have shown that newborns (in the first hour of life in some studies) preferentially look towards simple face-like patterns. Although the exact visual cues that elicit this preference remain unclear, unidimensional psychophysical properties of the stimuli, such as their spatial frequency spectra, cannot provide a complete explanation^{32–34}. One purpose of this early tendency to fixate on faces might be to establish bonding with adult caregivers. However, an equally important effect is to bias the visual input to plastic cortical circuits. This biased sampling of the visual environment over the first days and weeks of life might ensure the appropriate specialization of later developing cortical circuitry³⁵.

The relatively prolonged postnatal development of the human brain gives the opportunity for teaching and instruction by adults. However, to benefit from this from an early age, the infant must be attuned to such situations. From 3 months of age (and possibly earlier), infants orient more rapidly to peripheral visual targets when they are cued by a change in the direction of eye gaze of a centrally presented face^{36,37} or by an object that interacts with them in a contingent way³⁸. From 12

HABITUATION

A decrease in the behavioural response to a repeated, benign stimulus.

SACCADE

A rapid eye movement that brings the point of maximal visual acuity — the fovea — to the image of interest.

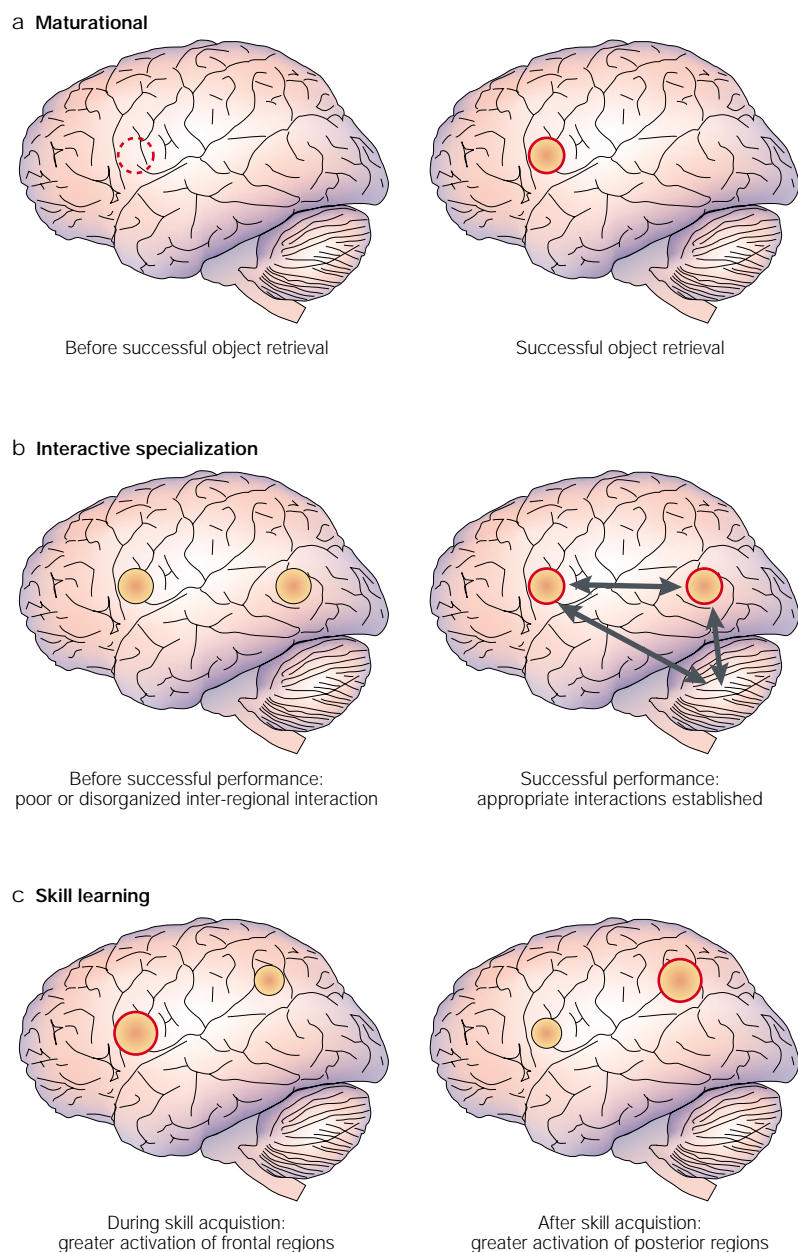


Figure 3 | Three accounts of the neural basis of an advance in behavioural abilities in infants. **a** | A maturational view in which the neuroanatomical maturation of one region, in this case the dorsolateral prefrontal cortex (DLPC), allows new behavioural abilities to emerge. Specifically, maturation of DLPC has been associated with successful performance in the object retrieval task (FIG. 1a)⁵⁰. Note that although the task itself involves activity in several regions, it is thought to be maturation of only one of these, the DLPC, that results in changed behaviour. **b** | An interactive specialization view in which the onset of a new behavioural ability is due to changes in the interactions between several regions that were already partially active. In this hypothetical illustration, it is suggested that changes in the interactions between DLPC, parietal cortex and cerebellum might give rise to successful performance in the object retrieval paradigm. In contrast to the maturational view, it is refinement of the connectivity between regions, rather than within a single region, that is important. According to this view, regions adjust their functionality together to allow new computations. **c** | A skill-learning model, in which the pattern of activation of cortical regions changes during the acquisition of new skills throughout the lifespan. In the example illustrated there is decreasing activation of DLPC and medial frontal cortex (pre-supplementary motor area), accompanied by increasing activation of more posterior regions (such as intraparietal sulcus), as human adults perform a visuomotor sequence learning task⁷⁷. It is suggested that similar changes might occur during the acquisition of new skills by infants. These three accounts are not necessarily mutually exclusive.

months onwards, infants also seem to interpret the behaviour of adults in terms of their goals or intentions^{39–41}. Early abilities such as these allow the infant to share ‘joint attention’ with adults to objects and events, providing perhaps the earliest form of education, and cues for early word learning.

An emerging picture from behavioural studies of infants is that they are born to learn, in the specific sense that simple tendencies to orient and attend to novel and socially relevant stimuli and events ensure that developing brain circuits receive more input from relevant sources. In this sense, the infant is an active participant in its own subsequent development.

Theories of human functional brain development Until the last decade, the study of human psychological development was largely conducted independently of any consideration of the underlying neural substrate. Similarly, human developmental neuroscience was largely descriptive, with little attempt made to understand the functional causes and consequences of changes in neuroanatomy. In this section, I review three viewpoints on human functional brain development that might shed light on processes of psychological change as well as clarifying the functional consequences of neuroanatomical changes during development.

The maturational perspective. Much of the research that has attempted to relate neural and behavioural development in humans has been from a maturational viewpoint in which the goal is to relate the anatomical maturation of specific regions of the brain, usually regions of cerebral cortex, to newly emerging sensory, motor and cognitive functions (FIG. 3a). Evidence concerning the differential neuroanatomical development of cortical regions is used to determine an age when a particular region will probably become functional. Success in a new behavioural task at this age is attributed to the maturation of a new brain region, and comparisons are often made between the behavioural performance of adults with acquired lesions and behaviours during infancy. One example of this approach comes from the neurodevelopment of visual orienting and attention. Several researchers have argued that control over visually guided behaviour is initially achieved by subcortical structures, but that with age and development, posterior cortical regions and finally anterior regions come to influence behaviour^{42–44}. The characteristics of visually guided behaviour in human infants over the first month of life resemble those observed in adult primates with cortical damage. For example, SACCADES at this age do not seem to be under endogenous control but are mainly elicited by external stimuli (exogenous); the visual tracking of moving stimuli is not smooth, but a series of separate re-foveations, and temporal visual field input dominates over nasal input. At around one month of age, infants go through a phase of ‘sticky fixation’ during which they have difficulty in shifting their gaze from one stimulus to another. Some have attributed this to the onset of competition between cortical and subcortical visuomotor pathways⁴⁴, whereas others have drawn

Box 2 | Genetic developmental disorders

In addition to their clinical importance, developmental disorders of genetic origin have been used to support the claim for innate computational modules in the human brain. However, recent reviews have concluded that there are few, if any, human genetic abnormalities that affect only specific regions of cortex⁵⁹. Rather, structural and functional neuroimaging usually reveals subtle but widespread differences in the brains of groups with developmental disorders. Similarly, claims of domain-specific cognitive deficits in such syndromes have been challenged, and replaced with hypotheses about different styles or modes of processing⁷³. Although there have been few behavioural studies of developmental disorders during infancy, those completed so far indicate discontinuities in the patterns of behavioural and cognitive deficits through postnatal development. For example, in one such disorder, Williams' syndrome, adults present with behavioural deficits in number tasks, but show surprising proficiency in some aspects of language. A question recently investigated is whether this pattern of specific deficits is also observed in Williams' syndrome infants, as would be expected if they have a damaged innate module for number. Standard infant paradigms for assessing number and object naming skills were used with toddlers with Williams' syndrome⁷⁴. The toddlers did not show the same behavioural profile as observed in adults with the syndrome, indicating that the profile of behavioural deficits in developmental disorders can change during ontogeny, and that it is not appropriate to characterize such deficits in terms of damaged 'innate modules'.

comparisons with BALINT'S SYNDROME in adults⁴⁵. Patients with Balint's syndrome have acquired bilateral parietal cortex damage and experience similar difficulties in 'disengaging' from one stimulus to saccade to another, indicating that immaturity of the parietal cortex in the infant has similar behavioural consequences. By 2–3 months of age, these markers of subcortical control are replaced by behavioural advances such as acquiring the ability to disengage easily from one stimulus to orient to another, consistent with the maturation of regions of the parietal cortex and associated structures. Further developments at 4–6 months, such as gaining the ability to inhibit reflexive saccades⁴⁶ and to make saccades in anticipation of a visual target being shown in a particular location^{47,48}, have been associated with developments in the frontal cortex. So, a general progression of maturation from posterior to anterior cortical regions might account for aspects of infant visually guided behaviour.

In another example, maturation within the frontal lobes has been related to advances in the ability to reach for desirable objects towards the end of the first year. As mentioned earlier, infants younger than 9 months often fail to accurately retrieve a hidden object after a short delay period if the object's location is changed from one where it was previously successfully retrieved (FIG. 1a). Instead, they perseverate by reaching to the location where the object was found on the immediately preceding trial⁴⁹. This error is similar to those made by human adults with frontal lesions and monkeys with lesions to the dorsolateral prefrontal cortex⁵⁰, leading to the proposal that the maturation of this region in human infants allows them to retain information over space and time, and to inhibit prepotent responses⁵¹. In turn, these developments allow successful performance in object retrieval paradigms. Although converging evidence for this claim comes from associations with resting frontal electroencephalographic responses⁵² and impairments in

children with a neurochemical deficit in the prefrontal cortex resulting from PHENYLKETONURIA⁵³, as yet no direct functional imaging on human infants during such object retrieval tasks has been possible.

Despite the successes of the maturational approach, and its support from some animal studies¹¹, there are reasons to believe that it might not explain all aspects of human functional brain development. For example, a view of human functional brain development in which regions mature sequentially cannot easily account for the dynamic changes in patterns of cortical activation observed during postnatal development, or for activity in frontal cortical regions during the first months of life. Furthermore, a comparison of the performances of pre-term versus full-term infants on the object retrieval task discussed above (FIG. 1a) indicates that the length of experience in the postnatal environment is critical⁵⁴. Evidence reviewed below indicates that consideration of the emerging interactions between regions of the brain is at least as important as the development of connectivity within a region.

The interactive specialization approach. In contrast to the maturational approach, in which behavioural developments are attributed to the onset of functioning in one region or system, an alternative viewpoint assumes that postnatal functional brain development, at least within the cerebral cortex, involves a process of organizing inter-regional interactions⁵⁵ (FIG. 3b). Referring to adult brain imaging data, Friston and Price⁵⁶ point out that it might be an error to assume that particular cognitive functions can be localized within a certain cortical region. Rather, they suggest that the response properties of a specific region are determined by its patterns of connectivity to other regions, and their current activity states. By this view, "the cortical infrastructure supporting a single function may involve many specialized areas whose union is mediated by the functional integration among them"⁵⁶. Extending this idea to development means that we should observe changes in the response properties of cortical regions during ontogeny as regions interact and compete with each other to acquire their roles in new computational abilities. The onset of new behavioural competencies during infancy will be associated with changes in activity over several regions, and not just with the onset of activity in one or more regions. In further contrast to the maturational approach, this view predicts that during infancy, patterns of cortical activation during behavioural tasks might differ from, and be more extensive than, those observed in adults. Within broad constraints, even behaviours that seem to be the same in infants and adults could involve different patterns of cortical activation.

Recent evidence indicates that the same behaviour in infants and adults can be mediated by different structures and pathways, and that there are dynamic changes in the cortical processing of stimuli during infancy. Experiments with scalp-recorded electrical potentials have indicated that, for both word learning and face processing^{57,58}, there is increasing spatial localization of selective processing with age or experience of a stimulus

BALINT'S SYNDROME

A neurological disorder caused by bilateral damage to the parieto-occipital region of the brain, characterized by disorders of spatial perception.

PHENYLKETONURIA

An inherited inability to metabolize phenylalanine which can result in brain and nerve damage leading to mental retardation.

Box 3 | Effects of early deprivation

Some of the classic animal studies on development and plasticity in the cortex have involved deprivation or distortion of early sensory input. Although such studies are clearly unethical in the case of human infants, the surgical reversal of infantile dense, bilateral cataracts offers the opportunity to assess the importance of visual experience over the first months of life. Recent work⁷¹ shows that visual acuity does not reach normal adult levels after bilateral congenital cataracts during infancy, even when the cataracts are removed at an early age. However, the improvements in acuity that are triggered by the onset of patterned visual input after surgery occur surprisingly rapidly, with significant improvement taking place in the first hours after treatment. These results indicate that acuity remains stagnant in the absence of patterned visual input and that the onset of such input triggers a rapid neural mechanism that partially compensates for the early deprivation. In the absence of any patterned input, this neural trigger is never present and acuity fails to develop. The effects of early deprivation also extend to perceptual and cognitive domains. For example, even after more than 9 years of subsequent visual experience, deficits in the configural processing of faces are observed following infantile cataracts⁷².

class. For example, in word recognition tasks, differences between known words and control stimuli are initially found over large areas, but this difference narrows to the leads over the left temporal lobe only when vocabulary reaches around 200 words, irrespective of maturational age⁵⁷. In parallel with changes in the patterns of regional activation are changes in the 'tuning' of individual regions. For example, when event-related potentials are recorded during passive exposure to faces, the resulting component that is sensitive to upright human faces (the N170) in adults is much more broadly tuned in infants. Specifically, in adults, the N170 shows a different amplitude and latency to human upright faces than to animal or inverted faces⁵⁸. In infants, the equivalent event-related potential component responds similarly to upright and inverted human faces⁵⁸. This evidence for dynamic changes in cortical processing during infancy is consistent with a process in which inter-regional interactions help to shape intraregional connectivity such that several regions together come to support particular perceptual and cognitive functions.

Further evidence for this viewpoint comes from studies of developmental disorders of genetic origin in which functional brain development unfortunately goes awry (BOX 2). Neuroimaging studies of groups with disorders such as autism and WILLIAMS' SYNDROME have yet to produce a clear consensus on the neural basis of these disorders⁵⁹. However, it is agreed from structural imaging studies that abnormalities in white matter are at least as extensive as those in grey matter⁶⁰, and from functional imaging that several cortical and subcortical regions are involved in these disorders^{59,61}. These general conclusions indicate that initial brain abnormalities are subsequently compounded by deviant patterns of interaction and connectivity between regions. This idea is supported by the observation that cortical activation patterns are different in patients with these disorders, even in areas of behaviour in which they perform as successfully as control subjects⁶². This view stands in contrast to the maturational account, in which developmental disorders could result in a deficit localizable to a particular cortical area with an associated specific cognitive deficit.

WILLIAMS' SYNDROME
A rare congenital disorder: symptoms include facial abnormalities and deficits in some cognitive skills.

GREEBLES
A category of computer-generated novel objects, originally designed as a control set for faces. Like faces, Greebles are all similar because they have the same number of parts in the same configuration.

The skill-learning hypothesis. Recent neuroimaging evidence from adults has highlighted changes in the neural basis of behaviour that result as a consequence of acquiring perceptual or motor expertise. One hypothesis is that the regions active in infants during the onset of new perceptual or behavioural abilities are the same as those involved in skill acquisition in adults. This hypothesis predicts that some of the changes in the neural basis of behaviour during infancy will mirror those observed during more complex skill acquisition in adults (FIG. 3c).

In contrast to more precocial mammals, one of the most striking features of human infants is their initial inability to perform simple motor tasks, such as reaching for an object. Work on complex motor-skill-learning tasks in adult primates shows that the prefrontal cortex is often activated during the early stages of acquisition, but that this activation recedes to more posterior regions as expertise is acquired^{63–65}. In addition to the examples of prefrontal involvement described earlier, activity in this region, or at least within the frontal lobe, has been reported in several infancy studies where action is elicited, and early damage to prefrontal structures has more severe long-term effects than damage to other cortical regions. For example, Csibra and colleagues²⁸ examined the cortical activity associated with the planning of eye movements in 6-month-old infants. They observed eye-movement-related potentials over frontal sites, but not over the more posterior (parietal) sites where they are normally observed in adults. Converging results are obtained when eye movement tasks are studied in infants with perinatal focal damage to the cortex. Infants with damage to the frontal quadrants of the brain show long-lasting deficits in visual orienting tasks, but infants with the more posterior damage that causes deficits in adults do not^{66,67}.

With regard to perceptual expertise, Gauthier and colleagues have shown that extensive training of adults with artificial objects, GREEBLES, eventually results in the activation of a cortical region previously associated with face processing, the fusiform face area⁶⁸. This indicates that the region is normally activated by faces in adults, not because it is prespecified for faces, but owing to our extensive expertise with that class of stimulus, and encourages parallels with the development of face processing skills in infants⁶⁹. The extent of the parallels between adult perceptual expertise and infant perceptual development remains unclear. However, in both cases, event-related potential studies have shown effects of stimulus inversion only after substantial expertise has been acquired with faces or greebles^{58,70}. Future experiments need to trace in more detail changes in the patterns of cortical activation during training in adults and development in infants.

From the view of functional brain development outlined in this section, it is interesting to study cases in which there has been a period of visual deprivation early in postnatal life (BOX 3). As predicted by this account, after the surgical restoration of vision following a period of deprivation, there is often rapid improvement in abilities to close to normal levels. However, in some important domains, such as the

NEAR INFRARED SPECTROSCOPY
A form of optical (light) imaging that entails placing sources and detectors on the head, and measuring the scatter or bending of light as it passes through the skull and brain.

configural processing of faces, recovery is never complete, with deficits still remaining after many years of visual experience. These findings indicate that the order in which motor and perceptual skills are acquired during development might be important, and that there are periods of development during which the brain is particularly sensitive to certain types of experience.

Conclusions and future prospects

Human postnatal functional brain development is not just the passive unfolding of a maturational sequence, but is an activity-dependent process, albeit guided and constrained by initial biases. Although progress has been made by considering functional brain development in terms of the sequential maturation of different cortical regions and their associated functions, it is becoming evident that new cognitive functions during infancy and childhood might be the result of emerging patterns of interactions between different regions. Some of these changing patterns of interactions between regions might also be characteristic of perceptual and motor skill learning in adults. By directing the infant to orient

and attend to certain types of external stimulus, some brain systems effectively 'tutor' others with appropriate input for subsequent specialization. In this sense, the human infant has an active role in its own functional brain specialization.

Further assessment of the three perspectives on human functional brain development presented here will require improved methods for non-invasive functional imaging, such as NEAR INFRARED SPECTROSCOPY, and more detailed computational models that generate predictions about both neuroanatomy and behaviour^{21,22}. Whatever the outcome of these investigations, a better understanding of functional brain development in human infants and children will have profound consequences for educational and social policies.

 Links

MIT ENCYCLOPEDIA OF COGNITIVE SCIENCES **Positron emission tomography** | **Magnetic resonance imaging** | **Autism** | **Perceptual development** | **Infant cognition** | **Neural development**

FURTHER INFORMATION **Johnson's research centre**

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