Cognitive and perceptual development during infancy

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Over the past seven years, the main advances in our understanding of infant development have involved the application of cognitive neuroscience methods such as neuroimaging and computer modelling. Results obtained using these methods have illuminated further the complex interactions between nature and nurture that underlie early postnatal development.

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Current Opinion in Neurobiology 2001, **11**:213–218

0959-4388/01/$ – see front matter

Abbreviation
ERP event-related potential

Introduction

Over the past fifty years, we have accrued considerable knowledge about the behavioural capacities of human infants. It is only during the past decade, however, that methods of cognitive neuroscience, such as functional imaging and computational modelling, have begun to be applied. Functional magnetic resonance imaging (fMRI) is now routinely applied to healthy children as young as six years, and there are even a few infant studies. In addition, the advent of easy-to-install, high-density scalp-recorded event-related potential (ERP) systems has opened a new vista of experiments on the temporal and spatial changes in cortical processing during infancy [1]. A second advance is the introduction of 'connectionist' and neural network models [2,3]. Connectionist networks are cognitive models loosely based on neural information processing, which can provide mechanistic accounts of the development of behaviour. When tightly coupled with experimental data, they offer a causal account of how and why behaviours emerge. Neural network models focus more on the functional consequences of changes in neural structure resulting from postnatal brain development. To illustrate these new directions in the field, as well as progress within more conventional approaches to infant developmental psychology, we review some of the topics in which the biggest advances have been made.

Vision and attention

Visual acuity is susceptible to the deleterious effects of early visual deprivation. Infantile cataracts (opacities that form on the cornea or, more typically, on the lens of the eye) that are not removed prior to six to eight months of age (when acuity and contrast sensitivity would normally be approaching adult levels) result in permanent deficits even after cataract removal. Recent work [4•] demonstrates that acuity does not reach normal adult levels in human infants with congenital cataracts 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 are surprisingly rapid, with most of the eventual improvement taking place in the first few hours after surgery. These results suggest that acuity remains stagnant in the absence of patterned visual input and that the onset of such input triggers a rapid neural mechanism that compensates (partially) for the early deprivation. In the absence of any patterned input, this neural trigger is never present and acuity fails to develop.

In the adult visual attention literature, there has been recent interest in 'object-centred' attention — that is, attention that is not directed to a spatial location but to an object. Although it is thought that infants from at least four months of age can covertly direct their attention to particular spatial locations, it was not known whether attention could be focussed on a specific object. Johnson and Gilmore [5] tested this by presenting eight-month-olds with dynamic visual stimuli that resembled objects. Following presentation of a cue on one part of the object, infants responded differently to targets presented elsewhere on the same object than they did to identical targets on objects that had not previously been cued. This shows that cueing attention to one part of an object highlights the whole object, just as it does in adults.

Action and space

Although there have been extensive studies of infants' perceptual abilities, considerably less work has focussed on action and on the brain processing that precedes action. Using eye movements as a simple form of action, several laboratories have examined saccade-related potentials to study the preceding brain activity. In adults, it is known that a sharply timed 'spike potential' recorded over parietal sites precedes the onset of most eye movements, and this potential reflects the dorsal visual pathway activity involved in planning and initiating the action. Surprisingly, this spike is not observed in infants aged four to six months [6], and only becomes apparent by 12 months [7], suggesting that saccades before that age are more dominated by subcortical pathways than was previously supposed.

Piaget [8] proposed that during the first few years of life, children progress from basing their actions on egocentric (body-centred) representations to allocentric (environment-centred) representations. Recent research has modified these views in several ways. First, there is now evidence for an earlier transition from sensory-centred (retinocentric) action to body-centred representations; such evidence comes from experiments in which infants make eye movements in response to a series of flashed targets [9,10]. Second, the degree of sophistication of infants' planning of actions is more task-dependent than was previously thought. For example, Kaufman and Needham [11] demonstrated that even six-month-old infants are capable of representing space in an allocentric frame of reference if the task demands are changed sufficiently. In their task, infants were habituated to a toy rotating at one corner of a tabletop. Following habituation, either the infant was moved to the opposite side of the table, or the toy was moved to the opposite table-corner (surreptitiously), or both. The results indicated that infants dishabituated whenever the object's location changed, but continued to habituate if only the egocentric relationship between the infant and the object changed. In a third line of research on infant action, several laboratories have examined the causes and consequences of the onset of self-produced locomotion (crawling). Among the widespread effects of the onset of crawling on social, emotional and cognitive development, it is likely to contribute to the infants' shift from egocentric to allocentric perceptions of the environment [12•].

Face perception and the origins of social cognition

Evidence indicates that there are regions of cortex in adults dedicated to face processing (see [13]), raising the possibility that there are 'innate modules' for this aspect of perception. However, several recent lines of evidence make this conclusion unlikely. First, although a series of studies has confirmed earlier findings that newborns will preferentially orient to simple face-like patterns [14], these preferences are only found in the temporal visual field (not the nasal), supporting the hypothesis that subcortical pathways are important [15]. Second, evidence from ERPs indicates that there are changes in the cortical processing of faces over the first year of life [16,17]. Third, although there is at least one report of a specific developmental deficit in face processing (prosopagnosia) [18], other studies have found that deficits in face processing resulting from perinatal brain damage usually co-occur with more general deficits in object processing and visual recognition [19].

Another area in which our current knowledge of the development of face processing has progressed is its significance for social cognition. For example, infants will orient more rapidly to peripheral visual targets when cued by the direction of eye gaze of a centrally presented face [20,21]. Although the neural and cognitive mechanisms underlying this ability are still under investigation, this initial finding offers a link between studies of face processing and studies of shared and joint attention during development [22].

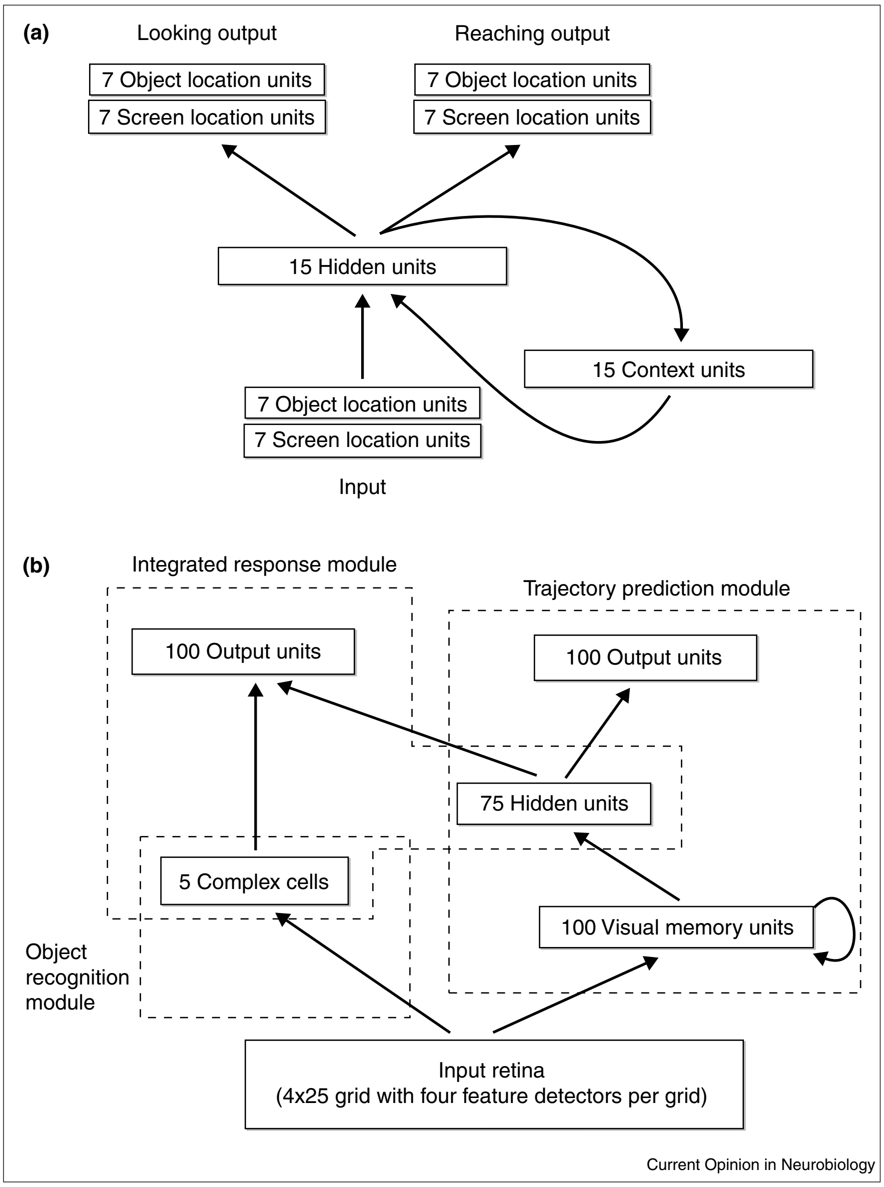
Another major thrust of recent research has concerned tracing the developmental origins of later social cognitive abilities. One question has concerned the cues and mechanisms that help infants to attribute psychological principles (such as mental states) to objects they observe. In other words, why and when is sensory information about a fellow human processed differently from that of an inanimate object? In one study, an otherwise inanimate robot that appeared to interact contingently with a watching 12-month-old infant was more effective in subsequently cueing the infant's attention to one side or the other than an equivalent robot whose interaction was not coordinated with the infant's behaviour [23]. Another study with infants of the same age used a visual habituation procedure to demonstrate that infants at this age can infer a goal for an incomplete action performed by a computer-animated circle with no obvious human-like features apart from its behaviour [24]. Still other research has been concerned with whether or not infants perceive the actions of adult humans in terms of the intention, or goal, of the adult concerned. For example, after having observed an adult perform several attempts to achieve a goal, at a later test session 18-month-old infants will re-enact the intended act (which they had never actually seen), and not the failed attempts. This was not the case when the same actions were performed by a mechanical device [25]. Thus, by at least the second year of life, children process the observed behaviour of other humans in terms of their intended goals. At earlier ages they may even attribute such goals to a wider range of objects [26].

Speech perception

A critical component of language acquisition is the ability to learn from the information present in the language input. However, this task is greatly complicated by the lack of natural markers in the sound stream that separates out meaningful units such as words. Despite the computational complexity of lexical segmentation, evidence suggests that by eight months infants can succeed at word segmentation in a sound stream [27] and can engage in the long-term storage of words [28]. The onset of word learning also changes the phonemic detail to which infants attend [29].

In a seminal study by Saffran *et al.* [30], eight-month-olds were presented with a computer generated, continuous sound stream of four three-syllable words made up of nonsense syllables randomly concatenated one after another. Saffran *et al.* found that after only two minutes of exposure to this continuous sound stream, infants would listen longer to a novel test stream containing non-words made from the same syllables as words but with a different order than to a novel stream made of familiar words. This was interpreted as evidence that the infants were sensitive to the transition probabilities between successive syllables in the words. In response to this claim, Marcus *et al.* [31] showed that seven-month-olds will transfer a repetition pattern of syllables from one sequence to a second test sequence that does not share any of the original syllables. Marcus argued that this was evidence of abstract rule-extraction rather than sensitivity to transitional probabilities because the infants had never been exposed to any of the test syllables and would therefore have no knowledge of the appropriate transition probabilities in the test phase. However, other studies interpret similar results more cautiously [32], and connectionist models of this task show that rule extraction is not necessary to produce the results observed [33].

Figure 1



Two alternative connectionist models of the emergence of object behaviours in infancy. **(a)** In the Munakata *et al.* model (see [44]), a network learns to predict the reappearance of a stationary object from behind a moving screen that temporarily occludes the object. Network performance is measured by taking the difference in response of the nodes coding the location of the hidden object when an object should be revealed and subtracting it from the response of the node when an object should not be revealed. An increase in this difference is interpreted as increased knowledge of hidden objects. This model shows that object representations that guide the response to objects can be graded and can arise though interactions within an environment. Representations required to elicit a looking response emerge before representations required to elicit a reach response. **(b)** The Mareschal *et al.* model (see [45•]) is more explicitly tied to the neuropsychological finding that visual object information is processed via two separate routes (see [52]). This model uses a combination of modules to implement dual-route processing. One route learns to process spatial–temporal information, whereas the other route learns to process feature information. Finally, a response module recruits and coordinates the representations developed by the other modules as and when required by a response task. The route specialisations emerge as a result of the different associative mechanism in each module. Delays on performance in tasks involving reach retrievals are attributed to the need to integrate information across multiple cortical modules in a voluntary directed reach. The boxes in the figure represent banks of nodes with specific functions in the networks.

Objects and numbers

Over the last five years, we have seen a shift from asserting exceptional early understanding of hidden objects and number to identifying some of the limitations of these early abilities [34•,35,36]. For example, while it was initially surprising that even young infants could succeed in keeping track of small numbers of objects when they were not directly visible (see e.g. [37]), it has since become clear that in succeeding in such tasks infants rely on spatial and temporal information, rather than on object-specific feature information [38–40]. In another example, four-month-old infants' ability to perceive two ends of a partially occluded object with common motion as a single unitary object had been regarded as evidence for innate knowledge of object properties. However, more recent studies have shown considerable development in this ability from birth to four months, and have revealed that the perception of object unity over this time depends on multiple different perceptual cues [41,42].

Several studies have revealed an apparent discrepancy between infants' knowledge of objects and their properties as assessed through various looking measures and that as assessed through their ability or otherwise to reach for objects [43]. Two connectionist models have been developed to try to account for this task-dependent dissociation (see Figure 1). In the first model, Munakata *et al.* [44] propose that success in reaching tasks comes later than in looking paradigms because of weak mental representations being sufficient only to support looking preferences. In the second model, Mareschal *et al.* [45•] suggest that the phenomenon results from the need to integrate information across the dorsal and ventral streams of cortical processing in directed reaching tasks, whereas such integration is not necessary in the current tasks utilising looking-time measures.

Categorisation and concepts

The developmental origin of concepts continues to be debated. Currently, this debate is focussed on two related issues. The first of these is the ability of infants to categorise visual inputs (e.g. into animals, vehicles etc.) on the basis of their perceptual similarity (animals tend to share features in common such as legs, heads etc.) or on more abstract knowledge (such as that vehicles are for travelling in). The second issue concerns the developmental formation of categories and whether it proceeds from global to basic categories (e.g. animals to cats) or vice versa [46,47]. Recent work has involved infants manipulating toy replicas of objects or animals. In one study, an imitation task is used in which infants are provided with a choice of toys and required to imitate an action. The results suggest that infants begin with very broad (global) categories based on the knowledge of functions of objects [48]. However, other work in which infants are allowed to manipulate hybrid objects that have both animal and vehicle features suggests that, even at 18 months, the classifications being made are based more on perceptual similarity than on taxonomic kind [49].

Connectionist network models can readily capture results from infant perceptual categorization experiments [50••,51]. For example, such models can explain unexpected idiosyncrasies of young infants' perceptual categorisation behaviour (e.g. the fact that the cat category excludes dogs but that the dog category does not exclude cats) in terms of the distribution of features in the stimuli used. The implication of these models is that the performance of young infants in visual preference tasks reflects rapid, data-driven, within-task learning rather than prior taxonomic knowledge. The performance of toddlers in toy manipulation tasks has yet to be modelled in this way.

Conclusions

Research on perceptual and cognitive development in infants is progressing rapidly. New approaches involving neuroimaging and computer modelling are opening up new vistas and perspectives on the complex interactions between nature and nurture during development over the first years of life.

Update

A recent publication has provided the first evidence for task-related EEG bursts in infants. Evidence from adults has demonstrated that there is a burst of gamma-band (40Hz) oscillatory activity in the brain whenever participants are required to perceptually 'bind' together different features to compose a single object. These bursts of oscillatory activity can be measured from the scalp using conventional ERP systems. Csibra and colleagues [53••] observed gamma bursts in eight-month-old infants when viewing illusory objects (such as "Kanisza" figures) that closely resembled those seen in adults with the same stimuli. In line with behavioural evidence that six-month-old infants do not perceive illusory objects, infants of this age did not show clear gamma-band bursting.

Debate continues on whether there is an 'innate module' for face processing, or whether our cognitive and neural specialisation for this ability results from experience. Some have suggested that experience over the first few months of life may be particularly important in setting up configural face processing in the cortex. Le Grand and colleagues [54••] were able to directly test this idea by studying face processing in patients that had congenital dense bilateral cataracts corrected within six months of birth. Even after more than nine years of subsequent visual experience, deficits in the configural processing of faces remain. This compelling example illustrates the importance of early experience for the functional specialisation of the human brain.

Another domain that has sometimes been characterised as an 'innate module' is number. In addition to the evidence discussed earlier about healthy infants' abilities with number judgements, some have pointed to evidence from genetic developmental disorders in which there are apparent specific deficits in number processing. In one such disorder, Williams Syndrome, adults present with behavioural deficits in number tasks, but have some aspects of language intact. 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. Paterson and colleagues [55••] used standard infant paradigms for assessing number and object naming skills in toddlers with Williams Syndrome. 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 characterise such deficits in terms of damaged 'innate modules'.

Acknowledgements

We acknowledge financial support from Medical Research Council Programme Grant (G97 15587), European Commission Research Training Network Grant (CT-2000-00065), Economic and Social Research Council Grant (R000239112) and Birkbeck College. We also wish to thank Gergely Csibra and Michelle de Haan for comments and discussion.

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