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Development of structure and function in the infant brain: Implications for cognition, language and social behaviour

Sarah J. Paterson^{a,*}, Sabine Heim^b, Jennifer Thomas Friedman^c, Naseem Choudhury^c, and April A. Benasich^c

^a Child Study Center, Yale University School of Medicine, 230 South Frontage Rd, New Haven, CT 06520–7900, USA

^b Department of Psychology, University of Konstanz, Germany

^c Infancy Studies Laboratory, Center for Molecular and Behavioral Neuroscience, Rutgers University, Newark, NJ, USA

Abstract

Recent advances in cognitive neuroscience have allowed us to begin investigating the development of both structure and function in the infant brain. However, despite the rapid evolution of technology, surprisingly few studies have examined the intersection between brain and behaviour over the first years of life. Even fewer have done so in the context of a particular research question. This paper aims to provide an overview of four domains that have been studied using techniques amenable to elucidating the brain/behaviour interface: language, face processing, object permanence, and joint attention, with particular emphasis on studies focusing on early development. The importance of the unique role of development and the interplay between structure and function is stressed throughout. It is hoped that this review will serve as a catalyst for further thinking about the substantial gaps in our understanding of the relationship between brain and behaviour across development. Further, our aim is to provide ideas about candidate brain areas that are likely to be implicated in particular behaviours or cognitive domains.

Keywords

Development; Brain; Cognition; Language; Imaging; Infants

1. Introduction

A rapidly expanding literature examines the role that different brain regions play in cognition and behaviour. Much of these data have come from animal models as well as lesion studies in animals and brain-injured patients. In addition, the body of research concerning the normal course of development for specific brain areas and their relation to skills in infancy is growing. The need for such research has been highlighted by the increasing emphasis on interdisciplinary approaches to cognitive neuroscience that encompasses the work of cognitive developmentalists, basic neuroscientists and imaging experts. However, the critical interdisciplinary studies examining brain and behaviour patterns prospectively and longitudinally across the first years of development have yet to be accomplished.

*Corresponding author. E-mail address: sarah.paterson@yale.edu (S.J. Paterson).

1.1. The importance of a multi-level approach

In order to fully understand brain and behaviour relations over the course of development, one must gather converging data from a variety of sources. The study of mature intact brains provides us with an idea of the endstate that the developing organism must reach. The morphological and physiological correlates of behaviour are much more easily defined and recorded in the adult than in the infant, so adult studies provide a rational starting point for the investigation of the developmental process. In addition, brain dysfunction provides a window onto which aspects of structure and function are necessary for the performance of particular tasks in adulthood. It is extremely important however, not to underestimate the role of development in this endeavour. One must consider the complex and still poorly understood processes that interact across early development to result in a normative brain, as well as how particular biological or genetic factors influence the brain's developmental trajectory. Animal models allow us to perturb the system as it develops and to study what effect this has on brain structure, brain function and behaviour. This is particularly valuable when lesions and malformations are present very early in development because, of course, the very best way to gather data on development is to study a developing organism. It is also critical to study both typically and atypically developing infants and children because changes in the developmental trajectory and the impairments to which they lead may highlight those aspects of structure and function which are decisive in achieving an optimal outcome.

1.2. Emerging methods for the study of developmental trajectories

In recent years, the refinement of existing methods and the development of state-of-the art brain-imaging methods has enabled scientists to ask well-focused questions about how the changing structure and connectivity of the brain influences emerging cognitive skills. One can now examine infant behaviour and measure brain structure and function either concurrently or very closely in time. Thus, changes in behaviour and brain function can be traced in relation to changes in brain structure. Several noninvasive brain-imaging techniques are currently available for use with younger children and infants. These include dense array electroencephalography/event-related potentials (EEG/ ERPs) and near infra-red spectroscopy (NIRS), both of which have excellent temporal resolution for assessing function (e.g., Benasich et al., 2006; Baird et al., 2002), as well as magnetic resonance imaging (MRI), which provides good spatial localisation for investigating changes in brain structure (e.g., Als et al., 2004). In addition, an emerging technique, arterial spin labelling (ASL), uses MRI methodology to measure cerebral blood flow while the brain is at rest, without the need for contrast agents (Detre and Aslop, 1999; Alsop et al., 2000). There are also a few studies that have successfully used functional MRI (fMRI) to examine brain activation in young children and babies when they are performing a cognitive task or passively listening to sounds (e.g. Durston et al., 2002; Dehaene-Lambertz et al., 2002). Developments in imaging technology are accompanied by continuing improvements in analysis methods. For example, two-source dipole modelling approaches have been proposed (Richards, 2004; Johnson et al., 2001) which can be based on independent and principal components analyses to improve accuracy of the source localisation of ERP signals. In order to accomplish this, investigators require head models appropriate for normal infants, which should include conductivity and volumetric estimates for scalp, skull, and liquid. As well as taking advantage of advances in individual techniques, researchers are beginning to use converging imaging methods to acquire both temporal and spatial information from the same adult participant during the same session (Anourova et al., 2001; Sutherling et al., 2001; Liebenthal et al., 2003; Huiskamp et al., 2004; Comi et al., 2005; Sammer et al., 2005). Unfortunately these simultaneous techniques are not yet adapted for use with infants and toddlers.

1.3. Structural development of the infant brain

In order to study development effectively, it is important to consider changes in brain structure as well as in brain function. Differences in the rate and extent of brain maturation are likely to have an effect on behavioural performance even within the normal range (Shaw et al., 2006). It is important to examine both individual variation in the typically developing population as well as differences in the relation between brain structure and function in atypically developing groups. For example, the increasing sophistication of brain-imaging methods, such as diffusion tensor imaging (DTI), now allows for investigation of white matter tracts in the brain. The rate of maturation of white matter in the developing cortex reflects increasing myelination of axons. This increasing myelination enables more efficient transmission of neural signals and, by consequence, faster information processing. In addition, growing connectivity between regions adds more fibres to white matter tracts. The size, structure, and positioning of these tracts provides information about inter- and intra-connectivity in different brain regions in both normally developing and clinical samples (Paus et al., 2001; Herbert et al., 2003). For example, mapping the microstructure of temporo-parietal white matter, Klingberg et al. (2000) observed decreased diffusion anisotropy in the left hemisphere associated with reading impairment. In typically developing 4- to 17-year-olds, it has been shown that there is an age-related growth in connectivity between sensory and motor areas in the posterior and anterior speech areas of the left hemisphere (Paus et al., 1999). In adults, individual differences in the learning rate for non-native speech sounds are correlated with white and grey matter volume in the left, and to a lesser extent, the right parietal lobe (Golestani et al., 2002).

As reviewed by Paus et al. (2001), the progress of myelination appears to follow a distinctive temporal and spatial pattern. Beginning at birth, myelination commences in the base of the brain with the pons and the cerebellar peduncles and then progresses to the posterior optic radiation and the splenium of the corpus callosum (1–3 months). It then continues moving forward to the anterior limb of the internal capsule and the genu of the corpus callosum at around 6 months-of-age. Finally between 8 and 12 months-of-age the frontal, parietal and occipital lobes begin to be myelinated. Given this progression over distinct brain areas, one can speculate that those infants whose brain development is more advanced than others, in terms of the degree of myelination, may attain certain cognitive abilities earlier than their age-matched counterparts with less developed myelination. In fact, a number of developmental disorders, including holoprosencephaly, show slower progression of myelination as compared to normally developing children (Barkovich et al., 2002; Dietrich et al., 1988; Pujol et al., 2004). However, individual differences in the degree of myelination and concurrent cognitive ability have not yet been studied.

ASL (e.g., Detre and Aslop, 1999; Alsop et al., 2000) has the capacity to provide interesting insights into the development of the brain, by allowing measurements of cerebral blood flow (CBF) without the need for contrast agents. Several studies have shown blood flow increases to areas involved in particular sensory-motor or cognitive tasks in adults (Bandettini et al., 1992; Ye et al., 1998; Yang et al., 2000; Wang et al., 2003) such as in the pre-frontal and occipital areas during working memory tasks (Ye et al., 2000). It has also been reported that the reduction in volume of CBF to the posterior parietal and posterior cingulate is correlated with the severity of symptomatology in patients with Alzheimer's Disease (Alsop et al., 2000).

Chugani and colleagues (Chugani and Phelps, 1986) used a more invasive technique, positron emission tomography (PET), to examine the changes in glucose metabolic patterns as a function of maturation. They demonstrated that functional changes in human infant cerebral metabolic rate were consistent with behavioural, neurophysiological, and anatomical alterations known to occur across infant development. Such studies are rare, as PET requires the use of contrast media as well as sedation. Thus, the use of such techniques is often limited to clinical samples.

Normal development was explored in the Chugani studies by identifying a subset of children with no identified pathology within a population who were given diagnostic scans based on clinical indications. In contrast to PET, ASL lends itself well to studies of normal development because it is non-invasive and should enable systematic mapping of changes in cerebral blood flow (a surrogate for metabolic rate) for different brain regions over development. It is likely that during periods of rapid structural and functional change in specific brain areas, metabolic demand would increase and thus produce measurable increases in local CBF blood flow. It remains unclear as to what the time course of metabolic demand and its surrogate, increased CBF, actually represent with regard to development of neural networks. Increases in CBF may precede maximal dendritic arborisation and formation of efficient interconnectivity or might reflect consolidation or pruning of connections, thus more efficient connectivity. Techniques like ASL as well as converging studies in appropriate animal models may well provide critical information about how optimal cortical development is accomplished (Wang et al., 2006).

1.4. Tracking development over time using well-defined tasks

Once good structural data has been obtained, it can be studied in relation to behavioural data from clearly defined tasks. Marker tasks are extremely useful in this endeavour (Johnson, 1997). Such tasks have been related to one or more brain regions in adults or non-human primates. It is important to choose tasks that work well throughout development, so that similar skills can be tapped in both infants and adults. If this is achieved, then it is possible to see how the relationships between behaviour and the putative brain areas that subserve it change over time. Suitable tasks include those commonly used in infancy research to measure discrimination, categorisation, and memory, such as habituation and preferential looking (see Benasich and Read, 1999). Tasks that are administered to assess established developmental milestones, such as object permanence and joint attention also provide useful data. Similar tasks (e.g., the well-known delayed matching-to-sample paradigm) have been used to conduct invasive studies with non-human primates, enabling tracing of neural pathways (Goldman-Rakic, 1987; cf. Bachevalier, 2001).

In this paper, we review studies from four domains: language, face processing, object permanence, and joint attention and, where available, use evidence from animal literature, and from studies using psychophysical tests and marker tasks with normally developing children and adults, as well as lesion studies. We aim to provide the reader with suggestions about the brain regions that might be of interest when carrying out imaging studies early in development. Although not an exhaustive review, it is hoped that this cross-section through the relevant literatures will serve as a helpful resource when developing hypotheses and will serve to stimulate the exploration of neglected domains.

Many developmental studies suggest potential models or mechanisms. However, in some areas, such as social development, little research is available that suggests possible brain regions that might underlie behavioural changes over development. Longitudinal developmental research is critical because defined regions of interest are an important starting point when developing hypotheses using neuroimaging methods.

1.5. The importance of developmental data

The emerging multidisciplinary approach to cognitive neuroscience and advances in neuroimaging techniques that allow visualisation of the living brain are both exciting and challenging. However, there are essential caveats that one should keep in mind when considering the role different brain regions may play in cognitive function. First, it is crucial to remember that the state of the infant brain, both in terms of structure and function, cannot and should not be derived from the adult brain (Paterson et al., 1999, Karmiloff-Smith, 1998, Elman et al., 1996). This is true for both the intact adult brain and the lesioned brain.

Thus, a lesion in adulthood may have an effect on a particular function at that time but this does not imply that the area subserves such a function during development. Johnson (1997) suggests an interactive specialisation approach, in which the process of organisation of the interactions between brain areas is stressed. Certainly, several investigators have shown that areas involved in the development of a function are not the same as those required for its maintenance. For example, Bates (1997) has shown that early in language development, damage to the right hemisphere has a bigger impact on comprehension than damage to the left hemisphere, contradicting what we would expect, given the adult literature. Additionally, the localisation of various cognitive functions changes as they develop; as attention develops from a simple orienting response to a mature executive function, areas associated with attention move from posterior regions to more anterior regions with age (Posner and Petersen, 1990). The importance of taking a developmental approach and avoiding assumptions that the functional structure of the brain is pre-existing in the infant cannot be over emphasised. However, this does not render futile the search for relationships between structure, function and behaviour in the developing system. It means only that one must use results from adult studies as a starting point or guide for identifying possible candidate areas that are important for development of a particular ability, rather than using the adult data as the definitive localisation tool.

Considering the defining role that development plays in shaping brain structure and function, it is also important to consider very carefully the nature of the behaviour being measured. Studies of atypically developing populations, such as children with Autism and Williams Syndrome (WS) have revealed that similar levels of behavioural competence can arise from very different underlying cognitive processes and/or different neural pathways. For example, individuals with WS appear to perform at normal levels on standardized face-processing tasks, such as the Benton Facial Recognition Test (Benton et al., 1983). However, when the cognitive processes underlying this behaviour are examined it appears that individuals with WS are processing on a featural level, whereas typically developing controls rely on configural processing. In an elegant study examining the effect of inversion on faces, buildings and geometric shapes, Deruelle et al. (1999) found that typically developing participants were slower to recognise inverted faces because this disrupts configural processing. However, this was not the case for individuals with WS and the observed difference is also manifested at the neural level. In two different studies, ERP responses of individuals with WS to faces were atypical. They did not show the typical increase in amplitude of the N170 component to inverted faces (Grice et al., 2001) and the early part of their ERP waves (100–200 ms after onset of the stimulus) to faces was abnormal (Mills et al., 2000). Taken together, these data show that despite seemingly normal performance of individuals with WS on behavioural tests of face processing, both the cognitive processes and their underlying neural bases are different from those seen in controls. This example highlights the importance of considering data from several sources when formulating hypotheses in cognitive neuroscience.

Given these two caveats—the importance of considering development and using well defined measures—the studies selected for review in this paper should be seen as providing suggestions about which brain areas may be useful to consider first when attempting to compare changes in brain structures with functional and behavioural changes across development. These candidate regions should not be taken as definitive localisations of function but theoretically based suggestions as to where one might begin to look for associations. One should also keep in mind inter-area connectivity and which networks are most likely to be interacting concurrently or recruited successively. It should also be noted that these are a rapidly evolving literatures and the studies included for particular brain regions should be considered as a logical start point to a current literature review.

Further, when considering which specific brain regions might underlie performance in the targeted cognitive domains, it is essential to attempt to link change in brain structure and function with cognitive performance concurrently as well as predictively in order to tease apart co-occurring and predictive influences. The development of a particular brain area may affect the development of a specific cognitive skill, or it could be that the development of a single cognitive skill may influence brain structure and function (and co-emerging abilities) more widely. Such patterns are seen in the sorting process of neural connectivity in the early brain as it assembles itself anatomically and functionally. Thus, it is likely that changes in brain structure and function interact with emerging behaviour. Determining the direction of these influences is key to further understanding the links between brain and behaviour.

1.6. Brain development in language, cognition, and social behaviour

In order to illustrate how converging methodologies and results from different fields can contribute to the development of hypotheses about the relationship between brain structure and cognitive function across development, this review will highlight four key areas pertinent to language, cognition, and social behaviour. Rapid auditory processing, face processing, object permanence, and joint attention will serve to illustrate how converging methodologies and results from different fields can contribute to the development of hypotheses about the relationship between brain structure and cognitive function across development. These areas have been singled out for several reasons including that fact that a number of studies have been conducted in these domains using techniques amenable to elucidating the brain/behaviour interface. Moreover, previous studies have suggested that performance on these measures in infancy may predict or have influence on later cognitive processes. For example, joint attention (JA) skills have a clear role in the development of language (e.g., Baldwin, 1993) and social cognition (Mundy and Acra, 2006). This is particularly clear in atypical development, when joint attention does not develop as it should. Toddlers with autism have difficulties with JA and this can disrupt both social cognition and language (Mundy and Neal 2001). Early deficits in rapid auditory processing also have been shown to have an impact on later language. Those infants who have greater difficulty in processing rapidly presented sounds are at great risk for later language impairment (Benasich and Tallal, 2002; Benasich et al. 2002, 2006). The acquisition of object permanence is an important milestone in cognitive development and is also a precursor to later executive functioning skills (Diamond, 2002). Working memory and the ability to control attention and inhibit automatic responses are important for many more complex tasks later in development (McCandliss et al., 2003). Face processing is a fundamental skill for human interaction, and faces are important even to newborn infants (Johnson et al., 1991a,b). However, this does not mean that these skills are fully developed at birth. On the contrary, face processing provides an excellent example of how localisation and specialisation of brain substrates can change over the course of development, as does the literature on joint attention and object permanence. Several of the domains also highlight how animal research can inform investigators studying human development. The usefulness of animal models is particularly highlighted by research into object permanence, which uses the same tasks with both humans and animals (Diamond and Goldman-Rakic, 1989; Diamond, 1991).

This is not an exhaustive review either within or across areas, but is intended to highlight critical domains in early development that, at this moment in time, illustrate how multidisciplinary research can inform our understanding of the developing relationship between brain and behaviour. Further, we hope that this review will provide a model of how one might use the existing literature as a starting point to generate specific hypotheses regarding the relations between brain and behaviour and thus, the neural bases of cognition. Table 1 provides an overview of the studies discussed in each domain. It illustrates what tasks were used and what brain regions have been suggested or implicated for each particular function.

2. Rapid auditory processing

The first cognitive domain that we consider is rapid auditory processing. This seemingly basic ability has been demonstrated to be important for language functioning. A large literature implicates basic difficulties in processing brief or rapidly occurring successive auditory cues, for both speech and non-speech stimuli, in the poor phonological skills which are observed in language-based learning disorders (LLI; for reviews see Leonard, 1998; Tallal, 2004; Tallal et al., 1998; Wright et al., 2000).

2.1. Behavioural studies

Across laboratories, research investigating basic auditory processing in individuals with specific language impairment (SLI) or dyslexia suggests that impaired perception and discrimination of auditory stimuli involving two or more rapidly presented transient elements hinders the development of normal language and reading abilities (Tallal and Piercy, 1974; Godfrey et al., 1981; Werker and Tees, 1987; Snowling et al., 1986; Stark and Heinz, 1996; McAnally and Stein, 1997). Further, several studies have suggested that efficient rapid auditory processing (RAP) ability is important for later language skill; performance on RAP tasks in infancy have been shown to relate to later language performance, both in normally developing infants and in those with a family history of language impairment (Benasich and Tallal, 2002; Molfese and Molfese, 1997; Trehub and Henderson, 1996). The ability to detect rapid changes in auditory information is critical for decoding language, as the majority of speech sounds (phonemes) constitute consonants, which are characterized by rapid frequency changes called formant transitions. There is converging evidence that highlights the possible functional neuroanatomy that might underlie differences in the ability to process rapidly presented auditory stimuli from postmortem studies, electrophysiological and neuroimaging research involving different age groups, as well as animal models (see Benasich and Leevers, 2003 for a review).

2.2. Electrophysiological studies

While it is not possible to lesion the brains of human infants, there is a natural experiment available to investigators in the form of infants who are at higher risk for LLI as a result of being born into a family with a history of SLI or dyslexia (Choudhury and Benasich, 2003; Benasich and Tallal, 2002; Lyytinen et al., 2004), or older children who have been diagnosed with some form of LLI. ERP studies have been conducted to investigate possible differences in brain responses to rapidly changing acoustic information between infants at familial risk for dyslexia and control participants. Guttorm and colleagues (Guttorm et al., 2001) found that the ERP responses elicited by stop consonant-vowel syllables (/ba/, /da/, and /ga/) differentiated the at-risk group from the controls, within a few days of birth. While infants from non-dyslexic families exhibited a prominent activation pattern over the left hemisphere, activation patterns reflecting syllable discrimination were greater over the right temporal and parietal areas in the at-risk group (see also Guttorm et al., 2003, 2005).

Similar effects have been seen in dense-array ERP paradigms for infants with a family history of SLI, although these studies are rare. Benasich et al. (2005) reported a mitigated change-detection response following a delayed negative wave in the ERP to rapidly occurring tones in 6-month-olds at risk for SLI. In the same vein, Friedrich et al. (2004) using stop-consonant syllables, found the change-detection response to be delayed in 2-month-old infants from SLI families compared to controls.

The ERP literature on children and adults suffering from LLI is characterized by atypical neural responses to rapidly presented acoustic information. Neville et al., (1993) reported an atypical early negative ERP component in a subgroup of SLI children who demonstrated poor auditory

temporal performance behaviourally. This component, time-locked to tones, was found to be reduced over the right hemisphere and delayed in latency, especially over temporal and parietal sites in the left hemisphere. A contralateral (to the stimulated ear) and anterior distribution of the negative wave was considered to reflect activity generated in the superior temporal gyrus, which encompasses Heschl's gyrus and the planum temporale. Of course, it is important to remember that source localisation using the distribution of responses on the scalp does not yet allow precise mapping of generator loci in the brain. This is particularly true in the case of the developing child, as appropriate brain templates are only just beginning to be generated (Richards, 2004). Advances in source localisation methods should enable us to pinpoint more accurately the area from which ERP components originate.

A promising component of EEG that is particularly suitable for examining rapid auditory processing is the mismatch response (MMR). The MMR is elicited by a passive oddball paradigm in which infrequent acoustic (deviant) stimuli are interspersed in a train of frequently presented (standard) sounds. This response is assumed to index a pre-attentive change-detection mechanism similar to the classic mismatch negativity described in older children and adults (Näätänen, 2001; see Leppänen et al., 2004 for a review). Studies employing stop consonant–vowel syllables report an attenuated mismatch response in learning-disabled or dyslexic children compared to typically developing controls (Kraus et al., 1996; Schulte-Körne et al., 1998; Bradlow et al., 1999). Likewise, in adults with a history of dyslexia, Kujala et al. (2000) observed atypical MMR patterns to auditory temporal information that were paralleled by poorer behavioural discrimination performance.

2.3. Functional neuroimaging studies

It has been commonly accepted that language comprehension is predominantly supported by the left hemisphere, particularly by the posterior temporal cortex. Functional imaging studies using PET or fMRI in healthy adults have demonstrated that the response to rapid auditory stimuli, in the form of rapid frequency transitions, is greater over the left hemisphere than the right, highlighting the importance of the left hemisphere for the processing of auditory information containing rapid transitions (Belin et al., 1998; Zaehle et al., 2004). Zaehle and colleagues reported exclusively left-sided activations in Heschl's gyrus and the planum temporale associated with the perception of both short gaps and stop consonant–vowel syllables. There is also evidence for collateral recruitment of left frontal cortical areas for the analysis of speech information (cf. Zatorre and Binder, 2000). Anomalous frontal activity to rapid successive auditory information has been observed in fMRI studies involving adults with dyslexia. While normal readers were found to exhibit increased activity in the left-prefrontal cortex in response to rapid relative to slow acoustic transitions, readers with dyslexia showed no differential activity (Temple et al., 2000). Similar evidence was obtained by Ruff et al. (2002) using natural speech.

There are also some exciting data from fMRI with 2–3 month-old infants that provide insights into auditory processing much earlier in development (Dehaene-Lambertz et al., 2002). Infants listening to speech, either forward or backward, in their native language displayed activation of the superior temporal and angular gyri, with greater activation on the left than the right. When babies were awake, the right prefrontal cortex was additionally activated. These areas are similar to those activated in adults, and interestingly the prefrontal cortex is activated in adult subjects who are retrieving verbal information from memory (Shallice et al., 1994).

2.4. Structural neuroimaging studies

In addition to deviations in functional topography, MRI investigations have revealed structural differences in LLI populations. The planum temporale, typically larger on the left in right-handed individuals, has long been thought to be an important substrate of left-hemispheric

language lateralisation (Geschwind and Levitsky, 1968). MRI studies have shown a tendency for unusual asymmetry (i.e., right hemisphere = left hemisphere or right hemisphere >left hemisphere) of the planum temporale in participants with SLI (Gauger et al., 1997) or dyslexia (Hynd et al., 1990; Larsen et al., 1990; Flowers, 1993). Structures of the perisylvian language region other than the planum temporale have also been found to differ in LLI individuals. For instance, Gauger et al. (1997) reported greater rightward asymmetry of planum+, which includes planum temporale and planum parietale, in children with SLI. Furthermore, these children showed a tendency towards atypical right-greater-than-left asymmetry of the pars triangularis, which coincides with parts of Broca's area. Robichon et al. (2000) demonstrated stronger right-hemisphere preponderance for Broca's region in adults with dyslexia compared to controls. The issue of neuroanatomical asymmetries is, however, not conclusive. There have been contradictory observations reported in both SLI (e.g. Preis et al., 1998) and dyslexia (e.g. Leonard et al., 1993). Such inconsistencies highlight the importance of considering findings across studies, including differing outcomes and conclusions, and identifying competing hypotheses when examining brain and behaviour relations.

Other studies implicate a more extensive network of brain areas in language processing. A study of children with SLI has revealed that the caudate nucleus is smaller in this group than in controls (Jernigan et al., 1991). In addition, lesions of the caudate nucleus in children appear to have a longer term and more deleterious effect on language than some left-hemisphere cortical lesions (Aram et al., 1985). The thalamus may also play a role in rapid auditory processing, as it is an important relay station for sensory inputs (Crosson, 1992).

2.5. Animal studies

Processing of rapid, successive auditory stimuli has also been studied in rodents using both electrophysiological and behavioural paradigms (Fitch et al., 1994; Frenkel et al., 2000; Friedman et al. 2004; Peiffer et al., 2004). Of course, animal models enable researchers to investigate the effects of induced lesions and malformations in a manner not possible with humans. In post-mortem studies of humans with dyslexia, neocortical malformations, including microgyria and ectopias, have been described (cf. Galaburda, 1993). These autopsy specimens also exhibited anomalies in thalamic nuclei (Galaburda et al., 1994), such that neurons of the (auditory) medial geniculate nucleus (MGN) were found to be smaller on the left side compared with the right; no such asymmetry was evident in control brains. Moreover, dyslexic brains were characterized by a relative excess of small neurons and a relative paucity of large neurons on the left side, specifically. The structural differences with respect to the MGN may be related to auditory rate processing dysfunctions described in individuals with LLI (Galaburda et al., 1996).

Analogous cortical malformations and MGN alterations are reproducible in animal models. A focal freezing lesion administered on postnatal day 1 in the rat (when neurons are still migrating in the cortex) results in 4-layered neocortical microgyria, similar to those found in humans with dyslexia (Fitch et al, 1997,1994). Several investigators have found that rats with induced cerebrocortical microgyria are impaired on rapid auditory processing tasks, both as mature animals (Clark et al, 2000,Fitch et al, 1997,1994;Herman et al. (1997) and across development (Friedman et al. 2004;Peiffer et al., 2004). Further, these malformations correlate with alterations in cell densities in the MGN. A study using mice bred to have ectopias further highlights the role of the MGN and auditory cortex in auditory temporal processing (Frenkel et al., 2000). Ectopic mice exhibited atypical intercranial ERP responses in the auditory cortex and MGN to rapidly presented auditory stimuli. Interestingly, such findings parallel those found in infants and children (Fitch et al., 2001; Heim and Benasich, 2006).

2.6. Summary

The findings reviewed here require further corroboration using converging methodologies, but it appears that candidate areas for investigating rapid auditory processing include the thalamus, caudate, and frontal areas as well as the more obvious temporoparietal speech areas in the left hemisphere. It is important to note that the left-hemisphere specialisation for language seen in many healthy adults is likely to be a product of a long period of development, so when studying infants and small children, laterality effects may not be present or only emerging (see Bates 1997, for an excellent discussion). Longitudinal research studies should therefore map the changing contributions of different brain areas over development. The development of improved source localisation tools should enable us to pinpoint the brain areas underlying language processing with more accuracy.

3. Face processing

Face processing is an extremely important skill for social interaction amongst humans. It appears to be a fundamental skill, with infants showing preference for faces from shortly after birth (Johnson et al., 1991a,b). In adulthood, we can recognise hundreds of faces and use this ability to read faces to rapidly surmise the emotions of others. Individuals who have difficulty with face processing during development, such as individuals with autism, also have significant difficulties with social interaction. (Klin et al., 2002). Given that face processing appears to be such a rapid and seemingly effortless process in normal adults, it has been of great interest to cognitive neuroscience researchers. In particular, this domain has been studied to investigate the degree of specialisation that might be present in the mature brain as a product of development. It also provides good examples of how increasing knowledge about localisation in animal models might contribute to our understanding of localisation over development.

3.1. Adult studies

Research with adults using neuroimaging techniques has demonstrated the presence of specialized networks for perceiving and recognising faces. However, there is very little functional imaging data from developmental studies in this domain. Neuropsychological evidence points to the importance for face processing in the fusiform face area (FFA), a discrete region in the inferior temporal gyrus. Adults with acquired damage to this area have difficulty recognising faces (e.g., Damasio et al., 1982). Moreover, in imaging studies of healthy adults, this area is more highly activated when passively viewing faces than objects, particularly in the right hemisphere (see for example, Kanwisher et al., 1997). It is likely that in adults the FFA is part of a more extensive functional network, comprising the FFA, superior temporal sulcus, and occipital face area (Haxby et al., 2000). In addition, animal studies have demonstrated that neurons that respond selectively to faces can be found in inferior temporal areas, superior temporal sensory areas, and the amygdala (Perrett. et al. 1988;Scalaidhe et al., 1999).

Data from a number of cases of adults with early occurring lesions that have led to impairment in face processing since infancy (developmental prosopagnosia) point to the increasing specialisation of the neural circuitry underlying face recognition. Behavioural impairments caused by early lesions do not appear to follow the expected pattern seen in adults with acquired damage or in imaging studies of normal adults. Behavioural data from individuals with developmental prosopagnosia reveal that their competency is not determined by the site or extent of the lesion. Those individuals with lesions at birth to the right hemisphere do not necessarily perform more poorly than those with left hemisphere lesions (see Mancini et al., 1994). This is not what one might expect given the increased activation of the FFA in the right hemisphere in adult imaging studies and provides an important reminder that plasticity and

changes in the degree of specialisation over development must be considered when choosing potential regions of interest.

3.2. Infant behavioural studies

Although there is sparse imaging data from face processing in infancy, we know behaviourally that infants are extremely interested in faces, preferring to look at faces rather than other shape stimuli even at birth (Johnson et al., 1991a,b; Johnson, 1997). Despite this early interest in faces, behavioural and electrophysiological studies have demonstrated that face processing has a protracted period of development and that the brain areas recruited for this task are likely to change with age.

Young infants appear to process face stimuli primarily using subcortical structures. In a study by Simion et al. (1998) neonates were tested under monocular viewing conditions so that responses to faces presented in the temporal and nasal hemi-fields could be compared. The infants oriented preferentially to face stimuli presented in the periphery, or temporal hemi-field. Such responses are mediated by the retino-tectal pathway. Later in development, it is likely that the ventral visual cortical pathway is recruited (see de Haan et al., 2002a, b for a full discussion). By 3 months of age, infants appear to have formed a perceptual category for faces, rather than storing individual exemplars. This is demonstrated by their ability to recognise a prototype face after having been presented with several individual exemplars in a visual familiarisation paradigm (de Haan et al., 2001). This categorical ability is likely to rely on cortical structures.

3.3. Infant electrophysiological and functional neuroimaging studies

It appears that the degree of functional specialisation for human faces seen in adults also emerges over development (Nelson, 2001). Such specialisation is characterized by several behavioural and neural correlates. There is a “face sensitive” negative component in the adult ERP which is prominent over the posterior temporal region at around 170 ms after stimulus onset. It has been suggested that the N170 reflects the structural encoding of faces (Eimer, 2000a,b). This component has a protracted period of development and is first observed in children at about 4 years of age (Taylor et al., 2001, 1999). Another marker for increasing specialisation is the face inversion effect, such that inverted faces are harder to recognise (Yin, 1969) and elicit different electrophysiological responses in adults than upright faces. ERP responses to inverted faces are generally of longer latency and higher amplitude in the mature brain (de Haan et al., 2002a,b). Behaviourally the inversion effect is present from about 4 months (Fagan, 1972). Finally, there is an effect of species on face processing. Adults find monkey faces more difficult to recognise than human faces and do not show an inversion effect for monkeys behaviourally (Pascalis and Bechevalier, 1998; Pascalis et al., 2002). This species effect is also present in ERP responses (de Haan et al., 2002a,b).

In infancy, however, functional responses to faces differ. The inversion effect (longer latency and higher amplitude electrophysiological responses to inverted versus upright faces) is not present in data from 6-month-old infants but is seen in that of 12-month-old infants. In addition, older infants show more of a “species specific effect.” While ERP studies reveal that the brain response to faces is evolving with development, they are unable to provide a good indication of changes in spatial distribution of brain activity. The data do, however, suggest that greater responses are seen in the posterior cortex and that between 3 and 12 months the distribution of responses shifts from medial to more lateral areas, as seen in adult responses (Halit et al., 2003). ERPs also reflect increasing specialisation for faces. It is likely that the somewhat separate processing stages for different aspects of a face as reflected in the infant P400 and N290 may be integrated into one component with development, namely the adult N170 (Halit et al., 2003). Such specialisation might also be reflected in the localisation of brain activity and

changes of the timing of responses. Therefore it is important not only to consider *where* responses occur but also *when* they occur.

There is one functional imaging study in infants that addresses the localisation of face processing. Two-month-olds were scanned using PET while viewing unfamiliar faces and a non-face stimulus (Tzourio-Mazoyer et al., 2002). This study revealed greater activation in the face condition in right inferior temporal gyrus, bilateral inferior occipital and parietal areas and left inferior frontal and superior temporal gyri. Interestingly, the authors also analysed cerebral blood flow as an index of cerebral maturation, and found that despite generally low metabolic activity when compared with more medial areas such as the precentral gyrus, the FFA was already being recruited as part of a specialized network. This functional study provides useful starting points for the selection of regions of interest for infant face processing. These include both adult “face areas” and areas not typically found in adult studies. These are indeed interesting findings but it should be noted that the infants who participated in this study had experienced hypoxic ischaemic encephalopathy and so the results should be treated with caution.

3.4. Animal studies

There have been a number of studies in monkeys investigating the localisation of possible face selective areas in the brain. Single cell electrophysiological recordings have demonstrated that the superior temporal sulcus (STS) in macaques contains many cells that respond to faces, and that response of these cells is modulated by face inversion as in humans (Harries and Perrett, 1991). A recent study, in which the implantation of electrodes into the brain was guided by findings from an fMRI study on the same animals, revealed that in one “face area” 90% of cells were face selective (Tsao et al., 2006). While macaques may not demonstrate links between face areas and language as in human infants, invasive studies such as these conducted over development could suggest where further research efforts may be best focused.

3.5. Summary

Taken together, these data suggest that the brain areas subserving face-processing change over the course of development. Results from behavioural studies with newborns suggest that responses to faces may be supported by subcortical structures, and so investigation of these structures is likely to be important very early in development. However, this presents a challenge because it is difficult to capture these areas with electrocortical measures. Therefore it will be necessary to conduct more fMRI studies with young infants. It is also important to note that infants recruit areas of the cortex for face processing not normally recruited in adulthood, namely language areas in the superior temporal gyrus and the left-inferior frontal gyrus. Tzourio-Mazoyer and colleagues (2002) argue that this might reflect the relevance of attention to faces for social interaction and language acquisition. Hence, it might be useful to study areas which are not typically implicated in adult studies, but which might be extremely important developmentally both within and across domains.

4. Object permanence

The development of object permanence—keeping track of objects even when they disappear from view—is an important milestone in cognitive development. However, the timing of its development has led to controversy. Research with infants as young as 3–4 months has demonstrated that infants can represent hidden objects (Baillargeon, 1995) but it is likely that the ability to apply this knowledge is a later developing skill (Diamond, 1990). For the purposes of this review we consider infants’ ability to search for displaced hidden objects. This demands organised action involving the ability to keep a representation in mind and the ability to inhibit

incorrect responses and as such appears to call upon precursors to important adult skills such as working memory and executive control (Diamond, 1990).

In infancy, one of the ways object permanence is assessed is by hiding an object and having the participant search for it after a varying delay. The A not B task assesses object permanence by having the participant search for an object in one of two locations. Once the search is successful, the hiding place is switched and the infant has to change his/ her response. If participants search at the location which was correct on a previous trial, they make the so-called “A not B error”. Successful completion of this task involves both short-term memory, in order to remember the location of the hidden object over a delay, and the ability to inhibit the pre-potent motor response to reach to the previously correct location (Goldman-Rakic, 1987; Diamond and Goldman-Rakic, 1989). The A not B task is a good example of a marker task because it can be used with infants, animals and adults with cognitive impairments and can be manipulated to examine the effect of context and delay on performance.

4.1. Infant and animal behavioural studies

Because of its flexibility, object permanence has been well studied using a multidisciplinary approach in humans and animals. A not B studies with both macaque monkeys (Diamond and Goldman-Rakic, 1989) and human infants (Baird et al, 2002; Bell and Fox 1992; Diamond and Goldman-Rakic, 1989) have suggested that the maturation of the frontal lobes plays an important role in the development of this skill and, in particular, the ability to tolerate increasing delays between hiding the object and starting to search. Diamond and Goldman-Rakic (1989) found that macaque monkeys with lesions in the dorsolateral prefrontal cortex performed poorly on an object permanence task with delays of more than 2–5 s, and that performance decreased to chance level with 10 s delays. Typically developing human infants showed the same pattern at 7.5–9 months, but were successful with the longer 10 s delay at 12 months. Diamond (1990) argues that dorsolateral prefrontal cortex plays an important role in integrating both the inhibitory skills necessary to prevent the infant reaching to the wrong hiding place and for remembering where the object was hidden.

Data from adults with frontal lobe damage, who were tested on the delayed response task, which has the same cognitive demands as the A not B task, support the findings from infants (Freedman and Oscar-Berman, 1986) but the infant study did not yield localisation data.

4.2. Infant electrophysiological and functional neuroimaging studies

Evidence of localisation is provided by a recent longitudinal study of 5- to 12-month-old infants. Baird et al. (2002) employed a pioneering technique that permits imaging of cerebral blood flow: NIRS. NIRS data were collected from sites F3 and F4 over the left and right frontal areas of the brain while the infants performed an object permanence task over successive visits. Comparisons were made between data collected on the first visit at which the child displayed object permanence and those collected on the visit just prior to the emergence of this skill. Baird et al. (2002) found significant differences in the concentration of oxyhemoglobin and total hemoglobin levels in the frontal areas of the brain, with higher concentrations detected when infant first displayed object permanence. Higher levels of oxyhemoglobin are thought to reflect increases in metabolic rate and thus in neural activity, suggesting higher levels of neural activity in the frontal lobes of infants when the object permanence task is completed successfully. The maturation of the frontal lobes and the corresponding increase in glucose metabolism appears to be important for the development of object permanence. This is supported by data from a landmark PET study of infants that demonstrated increases in glucose metabolism in the frontal and association cortices between 8 and 12 months, at just the time when object permanence emerges (Chugani and Phelps, 1986). Examination of the role of frontal areas in the development of object permanence has also been explored using EEG.

In an analysis of EEG power over the frontal lobes in 7–12 month old infants, Bell and Fox (1992) found that as infants' object permanence skills developed, allowing them to tolerate increasing delays, so too did the EEG power (the amount of electrical activity in particular frequency bands) recorded over the frontal lobes. The biggest difference in performance between those children who tolerated a delay and those who did not was seen at the age of 10 months, the age at which the biggest increase in frontal EEG power was noted in the successful group. Thus, the analysis of power in EEG is another useful tool for studying the development of brain function as it may be a marker for changes that occur as skills are being consolidated or acquired and has exquisite temporal resolution allowing the observation of a response in the tens of milliseconds (Bell and Fox, 1996, 1998; Fischer and Rose, 1994, Mundy et al., 2000).

4.3. Summary

Taken together, the data from both infants and non-human primates suggest that the ability to hold a representation of an object in mind and to inhibit incorrect responses, as assessed by object permanence tasks, may call upon various areas in the frontal lobes. It is likely that the maturation of these areas plays an important role in the development of this skill. In fact, changes in the frontal lobes appear to have far reaching effects on cognition, being implicated in attention (Rothbart et al., 1994), and language (Leonard, 1998), for example. So from this short review, one can see how studies with infants, animals and adults all point to the involvement of the frontal lobes, particularly the dorsolateral prefrontal cortex, in the attainment of object permanence, regardless of whether the data come from lesion studies or from EEG or NIRS. This discussion of performance on A not B tasks is a useful example of the way in which data from different sources can be evaluated for concordance, enabling the development of plausible hypotheses for new imaging studies. Future studies should further investigate the role of the prefrontal cortex in object permanence and new techniques from neuroimaging should be employed to chart the changing connectivity between areas over development.

5. Joint attention

While few studies have used converging methodologies to investigate the development of social cognition (see Saxe et al., 2004 for an excellent review of how neuroimaging might be applied to theory of mind), there are some interesting hypotheses about which areas of the brain might subservise developing competencies. Joint attention is a core social cognitive skill that plays a very important role in early language acquisition (e.g., Mundy and Gomes, 1998). Joint attention is "the ability to coordinate attention with a social partner" (Mundy et al., 2000, p. 325). It can be either initiated by the infant, calling an adult's attention to an object the infant is looking at, or the infant can follow the attention of an adult. It has been suggested that these two highly related skills are actually subserved by two different brain systems making the investigation of their development a very attractive project for cognitive neuroscience (Mundy et al., 2000; Mundy 2003).

5.1. Infant electrophysiological and functional neuroimaging studies

The ability to initiate joint attention (IJA) in infants has been found to be predictive of both IQ scores (Ulvund and Smith 1996) and receptive language ability (Mundy and Gomes, 1998) in childhood. Evidence for brain areas important for IJA has come from functional imaging studies, using PET and EEG analysis and from studies of infants with developmental disorders. A PET study of infants about to undergo surgery for epilepsy revealed that those who had higher levels of glucose metabolism in the left frontal cortex also performed better on an IJA task after surgery (Caplan et al., 1993). This suggests that frontal lobe function may play a role in IJA. In addition, a longitudinal study of EEG coherence in infants from 14 to 18 months of age described EEG data suggesting left frontal and left and right central activation was

associated with IJA ability at 14 and 18 months (Mundy et al., 2000). This finding was expanded upon by Henderson et al. (2002) who used dense array electrodes for their EEG recordings and found medial frontal cortical activation in both hemispheres was associated with better IJA performance. The authors also report that activation of orbitofrontal, temporal and dorsolateral cortex was related to IJA. Certainly in adults, the frontal lobes have been implicated in tasks involving memory as well as inhibiting visual regard to an object (McEvoy et al., 1993). In order to initiate JA, it is necessary to look away from the object of your interest and to engage your partner in the interaction. In addition, frontal lobes are known to be involved in circuits which drive positive social reinforcement both in adults (Thorpe et al., 1983) and in infants as young as 10 months (Fox, 1991; Fox and Davidson, 1987).

Responding to joint attention (RJA) appears to be a less complex skill and involves brain areas which subserve many cognitive functions early in development. In order to respond to a partner's call for joint attention the infant must be able to switch his or her focus of attention. Data from the Mundy et al. (2000) EEG study have implicated left parietal area activation and right parietal deactivation in RJA tasks. These areas have also been linked behaviourally to tasks that tap early attention shifting capacities in 4–6-month-old infants (Johnson et al., 1991a,b). The developmental progression of JA, from responding to initiating is paralleled by the shift in the localisation of attentional mechanisms from the posterior to the anterior of the brain (Posner and Petersen, 1990; Rothbart et al., 1994). This parallel nicely illustrates how changes in the functional organisation of the brain have an impact on cognitive function. As control of attention moves to more frontal areas, the infant is able to begin to modulate their own attention as well as engaging the attention of others more effectively and thus becomes a more effective social partner.

5.2. Summary

Despite the data suggesting that RJA is a less complex skill, this measure does have interesting links to later cognitive development. If an infant can respond to caregiver's direction of their attention then they are likely to be exposed to sources of rich environmental input and benefit from many opportunities to learn new words and concepts. Several studies have highlighted the importance of RJA for later language development (Baldwin, 1991, 1993; Mundy and Gomes, 1998), and it is interesting to note that in an ERP study investigating responses to known and unknown words, Mills et al., (1994) found that peaks in activation were found in frontal and parietal areas, the very same areas thought to be involved in JA. This combination of methods and the investigation of different cognitive skills highlight the value of a multi-disciplinary approach. The shared localisation of certain aspects of language and social cognitive function facilitates the formation of hypotheses about the possible shared cognitive mechanisms underlying these skills.

The studies reviewed here point to the importance of two distinct pathways in the brain used for joint attention tasks. The left parietal lobe appears to be implicated in responding to visual attention, whereas the frontal and temporal lobes play a role in initiating visual attention. These findings highlight the importance and utility of choosing behavioural tasks that measure clearly defined cognitive abilities. If one does not know what the behavioural task is measuring, then the characterisation of brain areas important for that ability is not possible. What remains to be added to this burgeoning work on joint attention is an investigation of structure, function and behaviour in the same individuals over the course of development. This would enable us to begin to explore the sequencing of changes in these three areas and to investigate how changes in timing effect the overall developmental outcome. In fact, such an approach would be useful in every domain of cognitive development. More advanced imaging and analysis techniques will allow us to look not only at discrete brain areas but also at changing connectivity

and the establishment of cortical circuitry used in particular tasks over development. These techniques should help prevent us from taking a static view of development.

6. General summary

We have reviewed data from four different cognitive domains: rapid auditory processing, face processing, object permanence, and joint attention to provide examples of how results from studies with animal and humans can assist in the generation of hypotheses concerning the neural bases of normal language, cognitive, and social development. Rather than being an exhaustive catalogue of the literature in these domains, the examples are intended to be used as a starting point when developing new hypotheses concerning links between behaviour and the brain areas that might subservise it. The examples highlight the important contribution data from different fields can make to successful investigations in developmental cognitive neuroscience.

In many of the areas of cognition reviewed, the literature points to the importance of the frontal lobes. This brain region plays a major role in a great many cognitive tasks and is of particular interest to developmentalists because of its protracted developmental course. As was mentioned in the section on object permanence, the period between 8 and 12 months is crucial in the development of the frontal lobes and is an excellent time at which to conduct studies which examine behaviour and brain function in parallel. In many cognitive domains, one sees a change in the brain areas recruited as an ability develops. For example, in face processing subcortical areas are recruited early in development but later a wider network is involved including the fusiform face area (de Haan et al., 2002a,b). The absence of such a shift might serve as an indicator of a developmental problem, and therefore might be a useful clinical tool. In addition, in development we should not take adult patterns for granted. Infants may well use brain areas that are traditionally not thought of as important for a particular skill. It has been demonstrated that language areas such as superior temporal gyrus and the left inferior frontal gyrus appear to be involved in face processing. When searching for brain and behaviour links developmental researchers should be aware that networks may be much more widespread early in development.

The brain areas that are recruited for language-related tasks, such as in rapid auditory processing, are extensive as would be expected given the complexity of the task. While it is important to investigate the role of the superior temporal lobes in language development, the importance of subcortical structures, such as the caudate nucleus, for this ability should not be overlooked. Although it is difficult to localise electrophysiological responses to deep cortical areas, technological advancements including dense array EEG and modelling of recruitment of brain areas across time (e.g. directed coherence) provide increasing support for this endeavour (Michel et al., 2004). Moreover, areas such as the caudate nucleus and the thalamic nuclei are clearly seen in structural and functional MRI, even in 6-month-old babies, so there is increasing opportunity to begin mapping their development in detail. Functional MRI may well be a useful tool for language research because babies appear to be able to tolerate auditory stimuli in an MRI environment, even when not attending fully (e.g. Dehaene-Lambertz et al., 2002).

The review of studies of joint attention highlights the importance of having a clear idea of the cognitive process the target behavioural task is measuring. Studies linking brain and behaviour in this domain have revealed that distinct brain areas are recruited when initiating and responding to joint attention. Responding to joint attention appears to rely on areas that are also seen in attention tasks, whereas initiating joint attention shares many areas of activation with language tasks. This domain provides rich opportunities for developmental studies and techniques, such as NIRS, which can be used while the child is active, and should yield increasingly interesting data. Such studies should track the changing localisation of function

as skills develop. For, example the shift from visual areas when the child responds to joint attention to frontal areas as the child is able to engage a partner in joint attention his/herself. In addition, structural imaging, especially DTI, should allow us to trace increasing neural connectivity between areas that we believe are linked cognitively.

The attainment of object permanence is an important cognitive milestone. However, the early executive control mechanisms underlying it, such as response inhibition and attentional control, are more relevant to later development. Future research should investigate how the frontal lobes interact with other brain areas to allow control of complex behaviour. The work on object permanence and rapid auditory processing also illustrates the important contribution of animal studies to making links between brain and behaviour. Animal studies enable us to perturb the cognitive system in controlled ways that are not possible within studies of human development (Fitch et al., 2001). Such studies highlight how quite small and seemingly delimited changes in brain structure and function can have large effects on the behavioural outcome. The object permanence data from imaging, animals and human infants, showing the importance of the prefrontal cortex for this task, are an excellent example of how converging methodologies can enable us to verify the presence of links between brain and behaviour.

Although recent advances in imaging techniques are extremely exciting, it is important to exercise caution when embarking on studies examining the interface between brain and behaviour, particularly in development. It is important not only to look at brain areas in isolation, but as suggested above to consider changes in the connectivity between areas across development. Techniques that allow us to trace neural connectivity will also be extremely useful in this domain, as it is likely that the networks used in the development of a skill will be different from those seen in the mature brain. The use of improved diffusion tensor imaging techniques (Paus et al., 2001;Ulug, 2002) alongside fine-grained behavioural tasks should enable investigation of the time course, as well as individual variation in such changes. One should always remember that brain and behaviour relationships are extremely complex and that behaviour is likely to rely on circuitry dispersed across the brain, rather than a distinct circumscribed area. As noted by Neville et al. (1993), “the developing organism displays a high degree of change both in different neural systems and in cognition, and thus provides an important opportunity to link variability in one trajectory to variability in the other.” However, the careful use of increasingly fine-grained behavioural assessments in conjunction with state-of-the-art brain imaging methods provides an unparalleled and increasing opportunity to obtain a clearer, more detailed picture of how neural development interacts with environmental influences across time to produce complex behaviours and individual variability in brain function.

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References

- Als H, Duffy FH, McAnulty GB, Rivkin MJ, Vajapeyam S, Mulkern RV, et al. Early experience alters brain function and structure. *Pediatrics* 2004;113 (4):846–857. [PubMed: 15060237]
- Alsop D, Detre JA, Grossman M. Assessment of cerebral blood flow in Alzheimer’s disease by spin-labeled magnetic resonance imaging. *Annals of Neurology* 2000;47 (1):93–100. [PubMed: 10632106]
- Anourova I, Nikouline VV, Ilmoniemi RJ, Hotta J, Aronen HJ, Carlson S. Evidence for dissociation of spatial and nonspatial auditory information processing. *Neuroimage* 2001;14 (6):1268–1277. [PubMed: 11707083]

- Aram DM, Ekelma B, Rose D, Whitaker H. Verbal and cognitive sequelae following unilateral lesions acquired in early childhood. *Journal of Clinical and Experimental Neuropsychology* 1985;7:55–78. [PubMed: 3980681]
- Bachevalier, J. Neural bases of memory development: insights from neuropsychological studies in primates. In: Nelson, CA.; Luciana, M., editors. *Handbook of Developmental Cognitive Neuroscience*. MIT Press; Cambridge, MA: 2001. p. 365-379.
- Baird A, Kagan J, Gaudette T, Walz KA, Hershlag N, Boas D. Frontal lobe activation during object permanence: data from near-infrared spectroscopy. *Neuroimage* 2002;16:1120–1126. [PubMed: 12202098]
- Baldwin DA. Infants' contribution to the achievement of joint reference. *Child Development* 1991;62(5):875–890. [PubMed: 1756664]
- Baldwin DA. Infants' ability to consult the speaker for clues to word reference. *Journal of Child Language* 1993;20(2):395–418. [PubMed: 8376476]
- Baillargeon, R. A model of physical reasoning in infancy. In: Rovee-Collier, C.; Lipsitt, LP., editors. *Advances in Infancy Research*. Ablex; Norwood, NJ: 1995. p. 305-371.
- Bandettini PA, Wong EC, Hinks RS, Tikofsky RS, Hyde JS. Time course EPI of human brain function during task activation. *Magnetic Resonance Medicine* 1992;25(2):390–397.
- Barkovich AJ, Simon EM, Clegg NJ, Kinsman SL, Hahn JS. Analysis of the cerebral cortex in holoprosencephaly with attention to the sylvian fissures. *American Journal of Neuroradiology* 2002;23:143–150. [PubMed: 11827887]
- Bates, E. Plasticity, localization and language development. In: Broman, SH.; Fletcher, JM., editors. *The Changing Nervous System: Neurobehavioral Consequences of Early Brain Disorders*. Oxford University Press; New York: 1997. p. 214-253.
- Bradlow AR, Kraus N, Nicol TG, McGee TJ, Cunningham J, Zecker SG, et al. Effects of lengthened formant transition duration on discrimination and neural representation of synthetic CV syllables by normal and learning-disabled children. *Journal of the Acoustical Society of America* 1999;106:2086–2096. [PubMed: 10530031]
- Belin P, Zilbovicius M, Crozier S, Thivard L, Fontaine A, Masure MC, Samson Y. Lateralization of speech and auditory temporal processing. *Journal of Cognitive Neuroscience* 1998;10:536–540. [PubMed: 9712682]
- Bell MA, Fox NA. The relations between frontal brain electrical activity and cognitive development during infancy. *Child Development* 1992;63:1142–1163. [PubMed: 1446545]
- Bell MA, Fox NA. Crawling experience is related to changes in cortical organization during infancy: evidence from EEG coherence. *Developmental Psychobiology* 1996;29:551–561. [PubMed: 8911771]
- Benton, AL.; de Hamsher, KS.; Varney, NR.; Spreen, O. *Contributions to Neuropsychological Assessment*. Oxford University Press; New York: 1983.
- Benasich, AA.; Leevers, HJ. Processing of rapidly presented auditory cues in infancy: implications for later language development. In: Fagan, J.; Haynes, H., editors. *Progress in Infancy Research*. 3. Erlbaum; Mahwah, NJ: 2003. p. 245-288.
- Benasich, AA.; Read, HL. Representation: picture or process?. In: Siegel, IE., editor. *Development of Mental Representation: Theories and Applications*. Lawrence Erlbaum Associates, Inc; Mahwah, NJ: 1999. p. 33-60.
- Benasich AA, Tallal P. Infant discrimination of rapid auditory cues predicts later language impairment. *Behavioral Brain Research* 2002;136:31–49.
- Benasich AA, Thomas JJ, Leppanen PHT, Choudhury N. The importance of rapid auditory processing abilities to early language development: evidence from converging methodologies. *Developmental Psychobiology* 2002;40:278–292. [PubMed: 11891639]
- Benasich AA, Choudhury N, Friedman JT, Realpe Bonilla T, Chojnowska C, Gou Z. Infants as a prelinguistic model for language learning impairments: predicting from event-related potentials to behavior. *Neuropsychologia* 2006;44(3):396–411. [PubMed: 16054661]
- Brooks R, Meltzoff AN. The importance of eyes: how infants interpret adult looking behavior. *Developmental Psychology* 2002;38:958–966. [PubMed: 12428707]

- Caplan R, Chugani H, Messa C, Guthrie D, Sigman M, Traversay J, et al. Hemispherectomy for early onset intractable seizures: presurgical cerebral glucose metabolism and postsurgical nonverbal communication patterns. *Developmental Medicine and Child Neurology* 1993;35:574–581. [PubMed: 9435773]
- Choudhury N, Benasich AA. The influence of family history and other risk factors on language development. *Journal of Speech Language and Hearing Research* 2003;46:261–272.
- Chugani HT, Phelps ME. Maturational changes in cerebral function in human infants determined by FDG positron emission tomography. *Science* 1986;231:840–843. [PubMed: 3945811]
- Clark MG, Rosen GD, Tallal P, Fitch RH. Impaired processing of complex auditory stimuli in rats with induced cerebrocortical microgyria. *Journal of Cognitive Neuroscience* 2000;12 (5):828–839. [PubMed: 11054924]
- Comi E, Annovazzi P, Silva AM, Cursi M, Blasi V, Cadioli M, et al. Visual evoked potentials may be recorded simultaneously with fMRI scanning: a validation study. *Human Brain Mapping* 2005;24 (4):291–298. [PubMed: 15678479]
- Crosson, BA. *Subcortical Functions in Language and Memory*. Guilford; New York: 1992.
- Damasio AR, Damasio J, Van Hoesen GW. Prosopagnosia: anatomic basis and behavioral mechanisms. *Neurology* 1982;32:331–341. [PubMed: 7199655]
- de Haan M, Nelson CA. Recognition of the mother's face by six-month-old infants: a neurobehavioral study. *Child Development* 1997;68:187–210. [PubMed: 9179998]
- de Haan M, Johnson MH, Maurer D, Perrett DI. Recognition of individual faces and average face prototype by 1- and 3-month-old infants. *Cognitive Development* 2001;16:1–20.
- de Haan M, Humphreys K, Johnson MH. Developing a brain specialized for face perception: a converging methods approach. *Developmental Psychobiology* 2002a;40:200–212. [PubMed: 11891633]
- de Haan M, Pascalis O, Johnson MH. Specialization of neural mechanisms underlying face recognition in human. *Journal of Cognitive Neuroscience* 2002b;14:199–209. [PubMed: 11970786]
- Dehaene-Lambertz G, Baillet S. A phonological representation in the infant brain. *Neuroreport* 1998;9:1885–1888. [PubMed: 9665620]
- Dehaene-Lambertz G, Pena M. Electrophysiological evidence for automatic phonetic processing in neonates. *NeuroReport* 2001;12:3155–3158. [PubMed: 11568655]
- Dehaene-Lambertz G, Dehaene S, Hertz-Pannier L. Functional neuroimaging of speech perception in infants. *Science* 2002;298:2013–2015. [PubMed: 12471265]
- Deruelle C, Mancini J, Livet MO, Casse-Perrot C, de Schonen S. Configural and local processing of faces in children with Williams syndrome. *Brain and Cognition* 1999;41:276–298. [PubMed: 10585239]
- Detre JA, Aslop DC. European perfusion magnetic resonance imaging with continuous arterial spin labeling: methods and clinical applications in the central nervous system. *Journal of Radiology* 1999;30:115–124.
- Diamond A. The development and neural bases of memory functions as indexed by the AB and delayed response tasks in human infants and infant monkeys. *Annals of the New York Academy of Sciences* 1990;60:231–267.
- Diamond, A. Normal development of prefrontal cortex from birth to young adulthood: cognitive functions, anatomy, and biochemistry. In: Stuss, DT.; Knight, RT., editors. *Principles of Frontal Lobe Function*. Oxford University Press; London, UK: 2002. p. 466-503.
- Diamond A, Goldman-Rakic P. Comparison of human infants and rhesus monkeys on Piaget's A not B task: evidence for dependence on dorsolateral prefrontal cortex. *Experimental Brain Research* 1989;74:24–40.
- Dietrich RB, Bradley WG, Zaragoza EJ, Otto RJ, Taira RK, Wilson GH, et al. MR evaluation of early myelination patterns in normal and developmentally delayed infants. *American Journal of Roentgenology* 1988;150 (4):889–896. [PubMed: 2450448]
- Durston S, Thomas KM, Yang Y, Ulug AZ, Zimmerman RD, Casey BJ. A neural basis for the development of inhibitory control. *Developmental Science* 2002;5 (4):F9–F16.
- Eimer M. The face-specific N170 component reflects late stages in the structural encoding of faces. *Neuroreport* 2000a;11:2319–2324. [PubMed: 10923693]

- Eimer M. Event-related brain potentials distinguish processing stages involved in face perception and recognition. *Clinical Neurophysiology* 2000b;111:694–705. [PubMed: 10727921]
- Elman, J.; Bates, E.; Johnson, MH.; Karmiloff-Smith, A.; Parisi, D.; Plunkett, K. *Rethinking Innateness: A Connectionist Perspective on Development*. MIT Press; Cambridge, MA: 1996.
- Fagan JF. Infants' recognition memory for faces. *Journal of Experimental Child Psychology* 1972;14:453–476. [PubMed: 4676459]
- Fischer, KW.; Rose, SP. Dynamic development of coordination of components in brain and behavior: a framework for theory and research. In: Dawson, C.; Fischer, KW., editors. *Human Behavior and the Developing Brain*. Guilford; New York: 1994. p. 3-66.
- Fitch RH, Tallal P, Brown CP, Galaburda AM, Rosen GD. Induced microgyria and auditory temporal processing in rats: a model for language impairment? *Cerebral Cortex* 1994;4:260–270. [PubMed: 8075531]
- Fitch RH, Miller S, Tallal P. Neurobiology of speech perception. *Annual Review of Neuroscience* 1997;20:331–353.
- Fitch, RH.; Read, H.; Benasich, AA. Neurophysiology of speech perception in normal and impaired systems. In: Jahn, A.; Santos-Sacchi, J., editors. *Physiology of the Ear. 2*. Singular Publishing Group, Inc; San Diego: 2001. p. 651-672.
- Flowers DL. Brain basis for dyslexia: a summary of work in progress. *Journal of Learning Disabilities* 1993;26:575–582. [PubMed: 8283123]
- Fox NA. If it's not left, it's right: electroencephalograph asymmetry and the development of emotion. *American Psychologist* 1991;46 (8):863–872. [PubMed: 1928939]
- Fox NA, Davidson RJ. Electroencephalogram asymmetry in response to the approach of a stranger and maternal separation in 10-month-old infants. *Developmental Psychology* 1987;23 (2):233–240.
- Freedman M, Oscar-Berman M. Bilateral frontal lobe disease and selective delayed response deficits in humans. *Behavioral Neuroscience* 1986;100:337–342. [PubMed: 3730139]
- Frenkel M, Sherman GF, Bashan KA, Galaburda AM, LoTurco JJ. Neocortical ectopias are associated with attenuated neurophysiological responses to rapidly changing auditory stimuli. *Developmental Neuroscience* 2000;11:575–579.
- Friedman JT, Peiffer AM, Clark MG, Benasich AA, Fitch RH. Age and experience-related improvements in gap detection in the rat. *Developmental Brain Research* 2004;152:83–91. [PubMed: 15351495]
- Friedrich M, Weber C, Friederici AD. Electrophysiological evidence for delayed mismatch response in infants at-risk for specific language impairment. *Psychophysiology* 2004;41:772–782. [PubMed: 15318883]
- Galaburda AM. Neuroanatomical basis of developmental dyslexia. *Neurological Clinics* 1993;11:161–173.
- Galaburda AM, Menard MT, Rosen GD. Evidence for aberrant auditory anatomy in developmental dyslexia. *Proceedings of the National Academy of Sciences* 1994;91:8010–8013.
- Galaburda, AM.; Schrott, LM.; Sherman, GF.; Rosen, GD.; Denenberg, VH. Animal models of developmental dyslexia. In: Chase, CH.; Rosen, GD.; Sherman, GF., editors. *Developmental Dyslexia*. York Press; Baltimore, MD: 1996. p. 3-14.
- Gauger LM, Lombardino LJ, Leonard CM. Brain morphology in children with specific language impairment. *Journal of Speech, Language, and Hearing Research* 1997;40:1272–1284.
- Geschwind N, Levitsky W. Human brain: left-right asymmetries in temporal speech region. *Science* 1968;161:186–187. [PubMed: 5657070]
- Godfrey JJ, Syrdal-Lasky AK, Millay KK, Knox CM. Performance of dyslexic children on speech perception tests. *Journal of Experimental Child Psychology* 1981;32:401–424. [PubMed: 7320677]
- Goldman-Rakic PS. Development of cortical circuitry and cognitive function. *Child Development* 1987;58 (3):601–622. [PubMed: 3608641]
- Golestani N, Paus T, Zatorre RJ. Anatomical correlates of learning novel speech sounds. *Neuron* 2002;35:997–1010. [PubMed: 12372292]
- Grice S, Spratling MW, Karmiloff-Smith A, Halit H, Csibra G, de Haan M, et al. Disordered visual processing and oscillatory brain activity in autism and Williams syndrome. *NeuroReport* 2001;12:2697–2700. [PubMed: 11522950]

- Guttorm TK, Leppänen PHT, Poikkeus AM, Eklund KM, Lyytinen P, Lyytinen H. Brain event-related potentials (ERPs) measured at birth predict later language development in children with and without familial risk for dyslexia. *Cortex* 2005;41:291–303. [PubMed: 15871595]
- Guttorm TK, Leppänen PHT, Richardson U, Lyytinen H. Event-related potentials and consonant differentiation in newborns with familial risk for dyslexia. *Journal of Learning Disabilities* 2001;34:534–544. [PubMed: 15503568]
- Guttorm TK, Leppänen PHT, Tolvanen A, Lyytinen H. Event-related potential in newborns with and without familial risk for dyslexia: principal component analysis reveals differences between the groups. *Journal of Neural Transmission* 2003;110:1059–1074. [PubMed: 12938027]
- Halit H, de Haan M, Johnson MH. Cortical specialization for face processing: face-sensitive event-related potential components in 3- and 12-month old infants. *NeuroImage* 2003;19:1180–1193. [PubMed: 12880843]
- Harries MH, Perrett DI. Visual processing of faces in temporal cortex: physiological evidence for a modular organization and possible anatomical correlates. *Journal of Cognitive Neuroscience* 1991;3(1):9–24.
- Haxby JV, Hoffman EA, Gobbini MI. The distributed human neural system for face perception. *Trends in the Neurosciences* 2000;4:223–233.
- Heim, S.; Benasich, AA. Developmental disorders of language. In: Chicchetti, D.; Cohen, D., editors. *Developmental psychopathology: risk, disorder, and adaptation*. 2. 3. Wiley; Hoboken, NJ: 2006. p. 268–316.
- Henderson L, Yoder P, Yale M, McDuffie A. Getting the point: electrophysiological correlates of protodeclarative pointing. *International Journal of Developmental Neuroscience* 2002;20:449–458. [PubMed: 12175886]
- Herbert MR, Ziegler DA, Makris N, Bakardjiev A, Hodgson J, Adrien KT, Filipek PA, Caviness VS. Larger brain and white matter volumes in children with developmental language disorder. *Developmental Science* 2003;6(4):F11–F22.
- Herman A, Galaburda AM, Fitch RH, Carter AR, Rosen GD. Cerebral microgyria, thalamic cell size, cell number, and auditory temporal processing in male and female rats. *Cerebral Cortex* 1997;7:453–464. [PubMed: 9261574]
- Hood BM, Willen JD, Driver J. Adult's eyes trigger shifts of visual attention in human infants. *Psychological Science* 1998;9:131–134.
- Huiskamp G, van Der Meij W, van Huffelen A, van Nieuwenhuizen O. High resolution spatio-temporal EEG-MEG analysis of rolandic spikes. *Journal of Clinical Neurophysiology* 2004;21(2):84–95. [PubMed: 15284598]
- Hynd GW, Semrud-Clikeman M, Lorys AR, Novey ES, Eliopoulos D. Brain morphology in developmental dyslexia and attention deficit disorder/hyperactivity. *Archives of Neurology* 1990;47:919–926. [PubMed: 2375699]
- Jernigan T, Hesselink JR, Sowell E, Tallal P. Cerebral structure on magnetic resonance imaging in language- and learning-impaired children. *Archives of Neurology* 1991;48:539–545. [PubMed: 2021369]
- Johnson, MH. *Developmental Cognitive Neuroscience: An Introduction*. Blackwell; Oxford: 1997.
- Johnson MH, Dziurawiec S, Ellis HD, Morton J. Newborn's preferential tracking of facelike stimuli and its subsequent decline. *Cognition* 1991a;40:1–21. [PubMed: 1786670]
- Johnson MH, Posner M, Rothbart M. Components of visual orienting in early infancy: contingency learning, anticipatory looking, and disengaging. *Journal of Cognitive Neuroscience* 1991b;3:335–344.
- Johnson MH, de Haan M, Oliver A, Smith W, Hatzakis H, Tucker LA, Csibra G. Recording and analyzing high-density event-related potentials with infants using the geodesic sensor net. *Developmental Neuropsychology* 2001;19(3):295–323. [PubMed: 11758670]
- Kanwisher N, McDermott J, Chun MM. The fusiform face area: a module in human extrastriate cortex specialized for face perception. *Journal of Neuroscience* 1997;17:4302–4311. [PubMed: 9151747]
- Kanwisher N, Stanley D, Harris A. The fusiform face area is selective for humans not animals. *NeuroReport* 1999;10:183–187.

- Karmiloff-Smith A. Development itself is the key to understanding developmental disorders. *Trends in Cognitive Sciences* 1998;2 (10):389–398.
- Klin A, Jones W, Schultz R, Volkmar F, Cohen DC. Defining and quantifying the social phenotype in autism. *American Journal of Psychiatry* 2002;159:895–905. [PubMed: 12042174]
- Klingberg T, Hedehus M, Temple E, Saltz T, Gabrieli J, Moseley ME, et al. Microstructure of temporoparietal white matter as a basis for reading ability: evidence from diffusion tensor imaging. *Neuron* 2000;25:493–500. [PubMed: 10719902]
- Kraus N, McGee TJ, Carrell TD, Zecker SG, Nicol TG, Koch DB. Auditory neurophysiologic responses and discrimination deficits in children with learning problems. *Science* 1996;273:971–973. [PubMed: 8688085]
- Kujala T, Myllyviita K, Tervaniemi M, Alho K, Kallio J, Näätänen R. Basic auditory dysfunction in dyslexia as demonstrated by brain activity measurements. *Psychophysiology* 2000;37:262–266. [PubMed: 10731777]
- Larsen JP, Høien T, Lundberg I, Ødegaard H. MRI evaluation of the size and symmetry of the planum temporale in adolescents with developmental dyslexia. *Brain and Language* 1990;39:289–301. [PubMed: 2224496]
- Leonard, LB. *Children With Specific Language Impairment*. The MIT Press; Cambridge, MA: 1998.
- Leonard CM, Voeller KKS, Lombardino LJ, Morris MK, Hynd GW. Anomalous cerebral structure in dyslexia revealed with magnetic resonance imaging. *Archives of Neurology* 1993;50:461–469. [PubMed: 8489401]
- Leppanen PHT, Lyytinen H. Auditory event related potentials in the study of developmental language-related disorders. *Audiology Neuro-Otology* 1997;2:308–340. [PubMed: 9390838]
- Leppanen, PHT.; Choudhury, N.; Benasich, AA.; Lyytinen, H. Neuroimaging measures in the study of specific language impairment. In: Verhoeven, L.; van Balkom, H., editors. *Classifications of Developmental Language Disorders: Theoretical Issues and Clinical Implications*. Lawrence Erlbaum Press; Mahwah, NJ: 2004. p. 99-137.
- Liebenthal E, Ellingson ML, Spanaki MV, Prieto TE, Ropella KM, Binder JR. Simultaneous ERP and fMRI of the auditory cortex in a passive oddball paradigm. *Neuroimage* 2003;19 (4):1395–1404. [PubMed: 12948697]
- Lyytinen H, Ahonen T, Eklund K, Guttorm T, Kulju P, Laakso ML, et al. Early development of children at familial risk for dyslexia—follow-up from birth to school age. *Dyslexia* 2004;10:146–178. [PubMed: 15341196]
- Mancini J, de Schonen S, Deruelle C, Massoulier A. Face recognition in children with early right or left brain damage. *Developmental Medicine and Child Neurology* 1994;36:156–166. [PubMed: 8132126]
- McAnally KI, Stein JF. Auditory temporal coding in dyslexia. *Proceedings of the Royal Society of London* 1997;263:961–965.
- McCandliss BD, Sandak R, Beck I, Perfetti C. Focusing attention on decoding for children with poor reading skills: design and preliminary tests of the word building intervention. *Scientific Studies of Reading* 2003;7:75–110.
- McEvoy R, Rogers S, Pennington R. Executive function and social communication deficits in young autistic children. *Journal of Child Psychology and Psychiatry* 1993;34:563–578. [PubMed: 7685360]
- Michel CM, Murray MM, Lantz G, Gonzalez S, Spinelli L, Grave de Peralta R. EEG source imaging. *Clinical Neurophysiology* 2004;115 (10):2195–2222. [PubMed: 15351361]
- Mills, D.; Coffey-Corina, S.; Neville, H. Variability in cerebral organization during primary language acquisition. In: Dawson, G.; Fischer, KW., editors. *Human Behavior and the Developing Brain*. Guilford Press; New York: 1994. p. 427-455.
- Molfese DL, Molfese VJ. Discrimination of language skills at five years of age using event related potentials recorded at birth. *Developmental Neuropsychology* 1997;13:135–156.
- Mills DL, Alvarez TD, St George M, Appelbaum LG, Bellugi U, Neville H. Electrophysiological studies of face processing in Williams syndrome. *Journal of Cognitive Neuroscience* 2000;12:47–64. [PubMed: 10953233]

- Mundy P. Annotation: the neural basis of social impairments in autism: the role of the dorsal medial-frontal cortex and anterior cingulate system. *Journal of Child Psychology and Psychiatry* 2003;44 (6):793–809. [PubMed: 12959489]
- Mundy, P.; Acra, F. Joint attention, social engagement and the development of social competence. In: Marshall, P.; Fox, N., editors. *The Development of Social Engagement Neurobiological Perspectives*. Oxford University Press; New York: 2006. p. 81-117.
- Mundy P, Gomes A. Individual differences in joint attention skill development in the second year. *Infant Behavior and Development* 1998;21:469–482.
- Mundy, P.; Neal, R. Neural plasticity, joint attention and autistic developmental pathology. In: Glidden, L.M., editor. *International Review of Research in Mental Retardation*. 23. Academic Press; New York: 2001. p. 139-168.
- Mundy P, Card J, Fox N. EEG correlates of the development of infant joint attention skills. *Developmental Psychobiology* 2000;36:325–338. [PubMed: 10797253]
- Näätänen R. The perception of speech sounds by the human brain as reflected by the mismatch negativity (MMN) and its magnetic equivalent (MMNm). *Psychophysiology* 2001;38:1–21. [PubMed: 11321610]
- Nelson CA. The development and neural bases of face recognition. *Infant and Child Development* 2001;10:3–18.
- Neville H, Coffey S, Holcomb P, Tallal P. The neurobiology of sensory and language processing in language impaired children. *Journal of Cognitive Neuroscience* 1993;5:235–253.
- Pascalis O, Bechavalier J. Face recognition in primates: a cross species study. *Behavioral Processes* 1998:87–96.
- Pascalis O, de Haan M, Nelson CA. Is face processing species-specific during the first year of life? *Science* 2002;296:321–1323. [PubMed: 11951038]
- Paterson SJ, Brown JH, Gsödl MK, Johnson MH, Karmiloff-Smith A. Cognitive modularity and genetic disorders. *Science* 1999;286:2355–2358. [PubMed: 10600749]
- Paus T, Zijdenbos A, Worlsey K, Collins DL, Blumenthal J, Giedd JN, Rapoport JL, Evans AC. Structural maturation of neural pathways in children and adolescents: in vivo study. *Science* 1999;283 (5409): 1908–1911. [PubMed: 10082463]
- Paus T, Collins DL, Evans AC, Pike LB, Zijdenbos A. Maturation of white matter in the human brain: a review of magnetic resonance studies. *Brain Research Bulletin* 2001;54 (3):255–266. [PubMed: 11287130]
- Peiffer A, Friedman J, Rosen G, Fitch RH. Impaired gap detection in juvenile microgyric rats. *Developmental Brain Research* 2004;152 (2):93–98. [PubMed: 15351496]
- Perrett DI, Mistlin AJ, Chitty AJ, Smith PA, Potter DD, Broennimann R, Harries M. Specialized face processing and hemispheric asymmetry in man and monkey: evidence from single unit and reaction time studies. *Behavioural Brain Research* 1988;29 (3):245–258. [PubMed: 3139010]
- Posner MI, Petersen SE. The attention system of the human brain. *Annual Review of Neuroscience* 1990;13:25–42.
- Preis S, Jäncke L, Schittler P, Huang Y, Steinmetz H. Normal intrasylvian anatomical asymmetry in children with developmental language disorder. *Neuropsychologia* 1998;36:849–855. [PubMed: 9740358]
- Pujol J, Lopez-Sala A, Sebastian-Galles N, Deus J, Cardoner N, Soriano-Mas C, et al. Delayed myelination in children with developmental delay detected by volumetric MRI. *Neuroimage* 2004;22 (2):897–903. [PubMed: 15193620]
- Robichon F, Levrier O, Farnarier P, Habib M. Developmental dyslexia: atypical cortical asymmetries and functional significance. *European Journal of Neurology* 2000;7 (1):35–46. [PubMed: 10809913]
- Richards JE. Recovering dipole sources from scalp-recorded event-related-potentials using component analysis: principal component analysis and independent component analysis. *International Journal of Psychophysiology* 2004;54:201–220. [PubMed: 15331212]
- Rothbart M, Posner M, Rosicky J. Orienting in normal and pathological development. *Development and Psychopathology* 1994;6:635–652.

- Ruff S, Cardebat D, Marie N, Démonet JF. Enhanced response of the left frontal cortex to slowed down speech in dyslexia: an fMRI study. *Neuroreport* 2002;19:1285–1289. [PubMed: 12151788]
- Sammer G, Blecker C, Gebhardt H, Kirsch P, Stark R, Vaitl D. Acquisition of typical EEG waveforms during fMRI: SSVEP, LRP, and frontal theta. *Neuroimage* 2005;24 (4):1012–1024. [PubMed: 15670678]
- Saxe R. Uniquely human social cognition. *Current Opinion in Neurobiology*. 2006;10.1016/j.conb.2006.03.001
- Saxe R, Carey S, Kanwisher N. Understanding other minds: linking developmental psychology and functional neuroimaging. *Annual Review of Psychology* 2004;55:87–124.
- Scalaidhe SP, Wilson FAW, Goldman-Rakic PS. Face-selective neurons during passive viewing and working memory performance of rhesus monkeys: evidence for intrinsic specialization of neuronal coding. *Cerebral Cortex* 1999;9 (5):459–475. [PubMed: 10450891]
- Schulte-Körne G, Deimel W, Bartling J, Remschmidt H. Auditory processing and dyslexia: evidence for a specific speech processing deficit. *Neuroreport* 1998;9:337–340. [PubMed: 9507979]
- Schulte-Körne G, Deimel W, Bartling J, Remschmidt H. Pre-attentive processing of auditory patterns in dyslexic human subjects. *Neuroscience Letters* 1999;276:41–44. [PubMed: 10586970]
- Shallice T, Fletcher P, Frith CD, Grasby P, Frackowiak RS, Dolan RJ. Brain regions associated with acquisition and retrieval of verbal episodic memory. *Nature* 1994;368 (6472):633–645. [PubMed: 8145849]
- Shaw P, Greenstein D, Lerch J, Clasen L, Lenroot R, Gogtay N, Evans A, Rapoport J, Giedd J. Intellectual ability and cortical development in children and adolescents. *Nature* 2006;440:676–679. [PubMed: 16572172]
- Simion F, Valenza E, Umiltà C, Dalla Barba B. Preferential orienting to faces in newborns: a temporal-nasal asymmetry. *Journal of Experimental Psychology: Human Perception and Performance* 1998;24:1399–1405. [PubMed: 9778830]
- Snowling MJ, Goulandris N, Bowlby M, Howell P. Segmentation and speech perception in relation to reading skill: a developmental analysis. *Journal of Experimental Child Psychology* 1986;41:489–507. [PubMed: 3734692]
- Snyder, KA.; Keil, A. Modulation of induced gamma oscillations by selective attention to faces of human infants. Poster Presented at the Annual Meeting of the Cognitive Neuroscience Society; 13–16 April; San Francisco. 2002.
- Stark RE, Heinz JM. Perception of stop consonants in children with expressive and receptive-expressive language impairments. *Journal of Speech and Hearing Research* 1996;39:676–686. [PubMed: 8844549]
- Sutherling WW, Akhtari M, Mamelak AN, Mosher J, Arthur D, Sands S, et al. Dipole localization of human induced focal after discharge seizure in simultaneous magnetoencephalography and electrocorticography. *Brain Topography* 2001;14 (2):101–116. [PubMed: 11797809]
- Tallal P. Improving language and literacy is a matter of time. *Nature Reviews Neuroscience* 2004;5 (9): 721–728.
- Tallal P, Piercy M. Developmental aphasia: rate of auditory processing and selective impairment of consonant perception. *Neuropsychologia* 1974;12:83–93. [PubMed: 4821193]
- Tallal P, Merzenich M, Miller S, Jenkins W. Language learning impairments: integrating basic science, technology and remediation. *Experimental Brain Research* 1998;123:210–219.
- Taylor MJ, Edmonds GE, McCarthy G, Allison T. Eyes first! Eye processing develops before face processing in children. *Neuroreport* 2001;12:1671–1676. [PubMed: 11409737]
- Taylor MJ, McCarthy G, Saliba E, Degiovanni E. ERP evidence of developmental changes in processing of faces. *Clinical Neurophysiology* 1999;110:910–915. [PubMed: 10400205]
- Temple E, Poldrack RA, Protopapas A, Nagarajan S, Salz T, et al. Disruption of the neural response to rapid acoustic stimuli in dyslexia: evidence from fMRI. *Proceedings of the National Academy of Sciences* 2000;97 (25):13907–13912.
- Thorpe S, Rolls E, Maddison S. The orbitofrontal cortex: neuronal activity in the behaving monkey. *Experimental Brain Research* 1983;49:93–115.
- Trehub SE, Henderson JL. Temporal resolution in infancy and subsequent language development. *Journal of Speech and Hearing Research* 1996;39:1315–1332. [PubMed: 8959616]

- Tsao DY, Freiwald WA, Tootell RBH, Livingstone MS. A cortical region consisting entirely of face selective cells. *Science* 2006;311:670–674. [PubMed: 16456083]
- Tzourio-Mazoyer N, De Schonen S, Crivello F, Reutter B, Aujard Y, Mazoyer B. Neural correlates of woman face processing by 2-month-old infants. *NeuroImage* 2002;15:454–461. [PubMed: 11798279]
- Ulvund S, Smith L. The predictive validity of nonverbal communication skills in infants with perinatal hazards. *Infant Behavior and Development* 1996;19:441–449.
- Ulug AM. Monitoring brain development with quantitative diffusion tensor imaging. *Developmental Science* 2002;5 (3):286–292.
- Wang J, Aguirre GK, Kimberg DY, Roc AC, Li L, Detre JA. Arterial spin labeling perfusion fMRI with very low task frequency. *Magnetic Resonance Medicine* 2003;49 (5):796–802.
- Wang, Z.; Fernandez-Seara, MA.; Alsop, DC.; Liu, W-C.; Benasich, AA.; Wang, J.; Detre, JA. CASL Perfusion MRI in Normal Infant Brain Development. International Society for Magnetic Resonance in Medicine, 14th Scientific Meeting; May 6–12; Seattle, WA. 2006. Program No. 3403
- Werker JF, Tees RC. Speech perception in severely disabled and average reading children. *Canadian Journal of Psychology* 1987;41 (1):48–61. [PubMed: 3502888]
- Wright BA, Bowen RW, Zecker SG. Nonlinguistic perceptual deficits associated with reading and language disorders. *Current Opinion in Neurobiology* 2000;10:482–486. [PubMed: 10981617]
- Yang Y, Engelien W, Xu S, Gu H, Silbersweig DA, Stern E. Transit time, trailing time, and cerebral blood flow during brain activation: measurement using multislice, pulsed spin-labeling perfusion imaging. *Magnetic Resonance Medicine* 2000;44 (5):680–685.
- Ye FQ, Berman KF, Ellmore T, Esposito G, van Horn JD, Yang Y, et al. H(2)(15)O PET validation of steady-state arterial spin tagging cerebral blood flow measurements in humans. *Magnetic Resonance Medicine* 2000;44 (3):450–456.
- Yin RK. Looking at upside-down faces. *Journal of Experimental Psychology* 1969;81:141–145.
- Zaehle T, Wustenberg T, Meyer M, Jancke L. Evidence for rapid auditory perception as the foundation of speech processing: a sparse temporal sampling fMRI study. *European Journal of Neuroscience* 2004;20 (9):2447–2456. [PubMed: 15525285]
- Zatorre, RJ.; Binder, JR. Functional and structural imaging of the human auditory system. In: Toga, A.; Mazziota, J., editors. *Brain Mapping: the Systems*. Academic Press; Los Angeles, CA: 2000. p. 365–402.

Table 1

Studies linking brain structure and function to behaviour

Method	Sample	Function	Brain structure/function	Reference
Rapid auditory processing	Right-handed adults ($n = 10$)	RAP	Left-biased asymmetry due to reduced activity of the right-hemispheric auditory cortex	Belin et al. (1998)
PET during passive auditory stimulation with non-verbal stimuli including rapid or temporally extended frequency transitions	Dyslexic adults ($n = 8$) Normal readers ($n = 10$)	RAP	Left prefrontal regions	Temple et al. (2000)
fMRI during detection of rapid and temporally extended non-speech analogues of consonant-vowel-consonant syllables	Right-handed adults ($n = 59$)	RAP	Larger white compared to grey matter volumes in parietal regions	Golestani et al. (2002)
MRI and behavioural training using rapidly changing vs. stationary non-linguistic sounds	Dyslexic brains ($n = 5$) Control brains ($n = 7$)	RAP	Medial geniculate nuclei	Galaburda et al. (1994)
Post-mortem study on human brains	Microgyric ($n = 6$) and sham-operated ($n = 6$) rats	RAP	Medial geniculate nucleus	Herman et al. (1997)
Induction of microgyria in the neonatal rat brain	Dyslexic adults ($n = 15$)	RAP	Temporal cortex (fronto-central electrodes)	Schulte-Körne et al. (1999)
ERP (MMN) to tone pattern contrasts	Normal spellers ($n = 20$)	RAP	Temporal cortex (left-hemisphere central electrode)	Leppanen and Lyytinen (1997)
ERP (MMN-like response) to Finnish pseudoword contrasts /ata/ (short duration) vs. /atta/ (long duration)	6-month-old infants with ($n = 18$) and without ($n = 17$) familial risk for dyslexia	RAP		
Consonant-vowel contrasts	3-month-old infants ($n = 24$)	Auditory change detection Phonological processing Categorical perception	Temporal cortex	Dehaene-Lambertz and Baillet (1998)
ERP (positive mismatch response) to within- and across- category syllable contrasts	3.5-day-old neonates ($n = 16$)	Phonetic processing	Temporal cortex (fronto-central sensors)	Dehaene-Lambertz and Pena (2001)
ERP (positive mismatch response) to phoneme changes (/pa/ vs. /ta/) when irrelevant speaker variation was present or absent	Newborn infants with ($n = 26$) and without ($n = 23$) familial risk for dyslexia	Phonetic processing	Left-hemisphere structures	Gutorm et al. (2001)
ERPs to syllables /ba/, /da/, and /ga/	Right-handed adults ($n = 59$)	Phonetic processing	Larger white compared to grey matter volumes in parietal regions	Golestani et al. (2002)
MRI and behavioural training using non-native syllables	6-month-old infants ($n = 22$)	Face recognition	Cortical midline structures	de Haan and Nelson (1997)
ERPs during viewing pictures displaying the mother's face and a stranger's face	Six-month-old infants ($n = 30$)	Attention Perceptual integration	Occipital sensors	Snyder and Keil (2002)
EEG (induced gamma-band activity) during watching of pictures displaying faces or objects	Adult subjects ($n = 5$)	Face perception	Fusiform gyrus	Kanwisher et al. (1999)
fMRI during presentation of pictures depicting inanimate, animate, and face stimuli				

Method	Sample	Function	Brain structure/function	Reference
PET during presentation of face and non-face stimuli	2-month-old infants Clinical cases ($n = 6$)	Face perception	Right inferior temporal gyrus Bilateral inferior occipital and parietal areas	Tzourio-Mazoyer et al. (2002)
ERP responses to upright and inverted faces	3-month-old ($n = 25$) and 12-month-old ($n = 26$) infants	Face perception	Left inferior frontal and superior temporal gyri	Halit et al. (2003)
Presentation of faces to the temporal and nasal hemifields	Neonates ($n = 26$)	Face perception	Posterior scalp region with shift from medial to lateral areas between 3 and 12 months Retino-tectal pathway	Simion et al. (1998)
Object permanence	Infants followed longitudinally from 5 to 12 months ($n = 12$) Human infants followed longitudinally from 7.5 to 12 months ($n = 25$) Intact and operated adult rhesus monkeys ($n = 10$) Infants followed longitudinally from 7 to 12 months ($n = 13$) Twelve-, 14-, and 18-month-old infants ($n = 96$)	Create and hold a mental schema of an object Integration of information while inhibiting a predominant response	Frontal cortex Dorsolateral prefrontal cortex	Baird et al. (2002) Diamond and Goldman-Rakic (1989)
Joint attention	EEG activity associated with performance on the A-not-B task Looking at adult's target in two conditions: open vs. closed eyes and headband vs. blindfold Attention shifts to eye direction of a digitized adult face EEG activity related to the ability to initiate joint attention EEG activity related to the ability to respond to joint attention	Integration of information while inhibiting a predominant response Psychological attribution/triadic relationship Visual/joint attention	Frontal sensors Prefrontal cortex Prefrontal cortex	Bell and Fox (1992) Brooks and Meltzoff (2002) Saxe (2006) Hood et al. (1998) Saxe (2006) Mundy et al. (2000)
	Nineteen-week-old ($n = 16$) and Twelve-week-old ($n = 11$) infants Infants followed longitudinally from 14 to 18 months ($n = 32$) Infants followed longitudinally from 14 to 18 months ($n = 32$)	Disengagement and re-engagement of attention Attracting the attention of another Attention switching	Bilateral central and left frontal sensors Parietal sensors	Mundy et al. (2000)

Note: EEG—electroencephalogram; ERP—event-related potential; fMRI—functional Magnetic Resonance Imaging; MMN—mismatch negativity; MRI—magnetic resonance imaging; PET—positron emission tomography; RAP—rapid auditory processing.