Developmental Science 5:3 (2002), pp 392–396

Developmental neuroimaging: a developmental psychologist looks ahead

Elizabeth S. Spelke

Department of Psychology, Harvard University, USA

The study of the mature human brain has moved forward at a rapid pace over the last 10 years, thanks in large part to the invention and use of a variety of neuroimaging methods. As the papers in this volume attest, many of these methods are now available for the study of the developing human brain, both in normal children and in children with a variety of developmental disabilities. These methods will allow developmental neuroanatomists and neurophysiologists to chart changes in brain morphology, long-range connectivity and activity as children grow and learn. Combinations of these methods, moreover, will allow developmental neuroscientists to probe specific brain processes and growth patterns. By combining functional magnetic resonance imaging (fMRI) or near infrared spectroscopy (NIRS) with event-related potentials (ERP) or magnetoencephalography (MEG), for example, investigators will be able to chart with considerable precision both where and when particular patterns of neural activity occur as children perform particular tasks. By combining diffusion tensor imaging (DTI) and fMRI, moreover, investigators will be able to relate developmental changes in connectivity across brain areas to changes in patterned activity within individual areas.

Knowledge of human brain development promises to grow at an unprecedented rate through the use of these methods and approaches. Here, however, I consider a different question: How will these methods for studying development of the brain contribute to knowledge of development of the human mind? Will developmental neuroimaging bring new insights to developmental psychology? I suggest an optimistic answer to this question: Developmental neuroimaging is likely to offer new insights into questions that have been central to developmental psychology for centuries. Developmental neuroimaging also may shed light on aspects of the mature human mind that have long eluded those who study adults.

Before turning to this suggestion, however, I must digress and consider how neuroimaging experiments have affected the study of mature psychological processes. Neuroimaging – particularly the functional brain imaging methods of positron emission tomography (PET), fMRI, ERP and MEG – has swept the field of human cognitive psychology over the last decade. Its contribution to understanding human cognitive processes, however, has been uneven. When functional neuroimaging methods have probed psychological functions that already were well understood on a behavioral level, they have provided rich and useful descriptions of the neural activity that accompanies these functions. These descriptions serve as *neural signatures* for the psychological mechanisms that accomplish the functions. In contrast, where functional neuroimaging methods have been used to study functions whose nature had eluded behavioral scientists, their findings have been as variable and inconclusive as those of the canon of behavioral research that preceded them.

To illustrate the first of these generalizations, consider functional neuroimaging studies of number processing in adults. Prior to the advent of fMRI, a wealth of behavioral evidence pointed to the existence of a cognitive system for representing and reasoning about number: what Dehaene (1997) calls 'number sense'. Evidence for number sense came from experiments on animals who were trained to discriminate particular numbers of objects or events (e.g. Meck & Church, 1983), on normal adults given number discrimination tasks under conditions that prevented verbal counting or other symbolic strategies (e.g. van Oeffelen & Vos, 1982), and on neurological patients who showed striking dissociations between number sense and other linguistic and calculation skills (e.g. Warrington, 1982). In all these populations, number representations were found to be abstract and amodal, to encompass increasing numerosities with no clear upper bound, and to be subject to Weber's Law: The discriminability of two numerosities depended on their ratio.

In the context of these behavioral findings, Dehaene and others have explored the neural mechanisms of number sense through coordinated studies using fMRI

Address for correspondence: Department of Psychology, Harvard University, 1130 William James Hall, 33 Kirkland Street, Cambridge, MA 02138, USA; e-mail: spelke@wjh.harvard.edu

(for high spatial resolution) and ERPs (for high temporal resolution). These studies have revealed that a predictable pattern of cerebral activity occurs at specific places and times during number processing tasks: number processing tasks elicit heightened activity bilaterally in the intraparietal sulcus and in other areas of inferior parietal cortex, and the activity begins very rapidly following onset of a numerical stimulus (e.g. Pinel, Riviere, LeBihan & Dehaene, 2001). The studies have not, however, overturned any of the conclusions of earlier behavioral work on number representations or yielded any radically new conclusions about the mechanisms of number sense.[1] Functional brain imaging has provided a set of detailed and useful neural signatures for a cognitive process that already was well specified at the behavioral level.

What do we learn from functional brain imaging studies of mature cognitive processes when we turn to questions that behavioral research has failed to answer? As an example, consider the question of domain-specificity in object recognition and categorization. Prior to the advent of functional brain imaging, psychologists debated whether the human mind contains distinct mechanisms for recognizing and reasoning about distinct kinds of objects such as faces, animals, food, houses, body parts and artifacts. For example, studies of normal and brain-damaged adults indicated that people recognize faces differently from many other objects (e.g. Farah, 1995), but they did not resolve whether this difference stemmed from a domain-specific face processor or from a more general processor whose operation was shaped by expertise (e.g. Diamond & Carey, 1986). Moreover, behavioral evidence for other domain-specific object processing systems pointed in contradictory directions, with some studies suggesting that adults have special systems for recognizing particular kinds of objects (e.g. Caramazza, 2000; Damasio, 1990) and other evidence suggesting they do not (e.g. Plaut, 1995).

In light of these controversies, it is not surprising that many functional neuroimaging experiments have tackled the issue of domain-specificity in object representation. I think it is fair to say that the same debates that raged in the behavioral research community are now consuming the neuroimaging communitity. Investigators using fMRI now argue about whether there is a brain region that is dedicated to the processing of faces (the 'fusiform face area' discussed by de Haan & Thomas in this issue) or whether this area is harnessed for all highly practiced and difficult object recognition tasks (see Kanwisher, 2000, and Tarr & Gauthier, 2000, for contrasting views). Moreover, these and other fMRI investigators now debate whether distinct brain regions are involved in the processing of faces, body parts, houses and artifacts, or whether larger regions are involved in more distributed processing of all these kinds of objects (see Kanwisher, 2000; Haxby, Gobbini, Furey, Ishai, Schouten & Pietrini, 2001). Functional neuroimaging experiments have helped to delimit the critical brain regions involved in object recognition tasks, but they have not resolved the longstanding debates over the nature of the mechanisms that accomplish these tasks.

These two cases illustrate a more general point about neuroimaging studies of human adults. Functional neuroimaging methods provide excellent ways to discover the *neural signatures* of mature cognitive processes. As they have been used so far, however, these methods have neither revolutionized nor dramatically enhanced our understanding of the *nature* of mature cognitive processes. Where understanding of behavior and cognitive function is limited, so is the ability to interpret the findings of functional neuroimaging experiments.

To return now to my initial question, what kinds of insights can developmental neuroimaging bring to developmental psychology? The question is risky, because scientists never know what any new method will provide until they use it, but I hazard two predictions. First, functional neuroimaging will influence developmental psychology more profoundly than its adult counterpart, providing new insight into patterns of continuity and change in psychological functioning. Second, functional neuroimaging of infants and children will shed light on aspects of mature cognitive and neural functioning by helping to break through some of the impasses in current studies of adults.

A central task of developmental psychology is to determine what aspects of human mental life and mental capacities are constant over human development and what aspects change with growth and experience. This task is simple to formulate, but many decades of behavioral research have shown that it is extremely difficult to accomplish, for two reasons. First, infants, children and adults may achieve the same behavioral outcomes through different underlying mechanisms. To take a current example, human adults, school children, preschoolers and infants who watch one object go behind a screen that previously moved over a second object, all

1 One new conclusion that has emerged from recent neuroimaging research is that number can be processed unconsciously: the same neural signatures of number representation that occur during conscious processing are observed during unconscious processing as well (Dehaene, Naccache, Le Clec, Koechlin, Mueller, Dehaene-Lambertz, van de Moortele & LeBihan, 1998). Nevertheless, this conclusion too was established through behavioral research – reaction-time studies of priming – prior to its investigation by neuroimaging methods.

infer that two objects now stand behind the screen (see Wynn, 1998, for review). Developmental psychologists do not agree, however, whether all these populations arrive at this inference in the same way. Some believe that infants use their sense of number to represent the scene and engage in the same process of non-symbolic arithmetic as do adult humans and other animals (e.g. Wynn, 1998). Others believe that radically different processes underlie the superficially similar accomplishments of the infant, child and adult (e.g. Simon, 1997; Carey & Xu, 2001). Both positions are tenable, because many different types of mechanism could serve to keep track of two objects that are hidden behind a screen.

Second, infants, children and adults may exhibit different behavioral capacities by relying on a constant set of mechanisms that express themselves differently at different ages. Continuing with number as an example, the ability to represent large numerosities is greatly enhanced when children come to use and understand verbal counting (e.g. Fuson, 1988; Wynn, 1990), but what is the nature of this effect? Some suggest that counting and non-counting children possess the same number concepts and mechanisms, but that counting allows children to apply those concepts more precisely (Wynn, 1990). Others suggest that counting changes children's number concepts more profoundly and allows them to construct a qualitatively new notion of what number is (e.g. Carey, 2001; Spelke, 2000). Both positions can be maintained, because the behavioral change that counting brings could have multiple underlying sources.

Although behavioral research has gone some distance toward resolving these questions, debates about continuity and change are hard to settle conclusively through behavioral experiments, because the relationship between underlying psychological processes and their behavioral outcomes is multifaceted and complex. Here, the introduction of functional neuroimaging methods may help considerably. As I noted above, functional neuroimaging studies of human adults provide specific and detailed signatures of number representations, and these signatures give developmental scientists specific things to look for in children and infants. If infants and children construct the same number representations and engage the same numerical processes as adults, for example, then we might expect to find the same signature activations in young children tested in Wynn's (1992) 'one plus one' experiments with infants as in Dehaene, Spelke, Pinel, Stanescu and Tsivkin's (1999) studies of mental calculation in adults. If new number representations emerge with the development of counting, then the signatures of these representations should be present only in children who have learned to count. Functional neuroimaging experiments therefore promise to enhance efforts to arrive at appropriate descriptions of continuity and change over human mental development.

By focusing on number development, I have illustrated the promise of developmental neuroimaging in a domain where adult cognitive functioning is fairly well understood. The promise of developmental, functional neuroimaging may be even greater, however, when we turn to processes that are not well understood in adults. To illustrate, consider again whether the brain and mind are organized into distinct, domain-specific systems for recognizing and reasoning about objects of different kinds. Although most previous studies addressing this issue have focused on adults, I believe that the most promising experiments would use combined behavioral and functional brain imaging methods with infants and children. If the mind is designed to accommodate a set of distinct, domain-specific processors, then the neural signatures of the mechanisms that process faces, body parts and other privileged categories might appear early in development, before the acquisition of expertise. In contrast, if the mind initially learns about all kinds of objects in the same way, and then shapes its perceptual processing of objects in particular domains through the growth of expertise, the same neural signatures should underlie infants' processing of all kinds of objects. By testing these contrasting predictions, developmental research may serve to cut through a controversy that has proved difficult to resolve through research on adults.

From the standpoint of developmental psychology, functional neuroimaging methods have three features that distinguish them from behavioral methods as tools for studying developmental continuity and change. First, neuroimaging methods provide rich, structured data. Most behavioral studies of children pose simple, yes/no questions: do infants discriminate 8 objects from 16? do preschool children know that 3 plus 2 is 5? Because there are many distinct representations and processes that could underlie either ability, behavioral experiments are open to multiple interpretations. In principle, functional neuroimaging experiments are open to multiple interpretations as well, but in practice, the wealth of data they provide tends to narrow the space of plausible interpretations.

Second, functional neuroimaging experiments allow developmental scientists to investigate young children's cognitive capacities in situations that place few extraneous demands on attention and memory. Perhaps the first rule of developmental research is that the capacities young children exhibit depend in part on the tasks they must perform: the greater the task's demands, the less competent children appear to be. This is the primary reason why some of the best evidence for perceptual and cognitive capacities in infants comes from studies using the simplest tasks, such as preferential looking studies in which infants simply observe objects repeatedly until their looking time declines, and then their looking times to novel events are measured (e.g. Baillargeon, 1999; Spelke, 1985). These studies give evidence for greater abilities to represent objects than do studies that require children to reach for objects (Piaget, 1954), or open doors to get to them (Berthier, DeBlois, Poirier, Novak & Clifton, 2000), in part because the latter studies challenge infants in multiple ways at once: infants must keep track both of the objects that are hidden and of the actions they must perform. Even preferential looking methods, however, rely on infants' differential behavior of looking or not looking at events, and most of these studies only tell us what infants perceive, remember and infer when they are bored!

An ideal experiment in cognitive development would test young children in a state of full attention and with no behavioral task to distract them. These conditions can never be achieved in a behavioral experiment, however, because nothing in the child's overt behavior would reveal what she perceives or thinks. In contrast, the ideal experimental conditions can be approached if we turn from behavioral to neuroimaging methods. Although some functional brain imaging experiments present subjects with complex tasks, many studies present simple tasks or no task at all. FMRI studies using free viewing methods, in which patterns of neural activity are measured while subjects simply look at an array of objects or events, have served to investigate a variety of perceptual and cognitive abilities in adults (see Kanwisher, Downing, Epstein & Kourtzi, 2001, for review). Although these methods must be used cautiously with younger participants to ensure that children process the displays with full attention, ERP experiments using free viewing methods already are providing valuable information about the perceptual and cognitive capacities of infants and young children, as are ERP experiments using simple, structured tasks (see de Haan & Thomas, this issue). In the domain of number processing, these methods have begun to test, in children, for the presence of the neural signatures of number processing found in adults (Temple & Posner, 1998).

This leads to the third distinctive feature of functional neuroimaging methods for developmental research. A recurrent problem in developmental psychology stems from the fact that different tasks and measures often must be used with children of different ages: the reaction time measures that work well with adults often work less well with young children and can't be used at all with infants; the looking time measures that work well with young infants often work less well with older children. Functional brain imaging experiments using simple methods, in contrast, allow one to present the same events and task context to subjects of all ages. Developmental changes in performance therefore can be more confidently attributed to changes within the child, rather than to changes in the task context.

Putting these features together, functional neuroimaging methods provide new tools for attacking one of the developmental psychologist's two oldest tasks: to chart both what is constant and what changes in children's mental capacities and processes. As this task is accomplished, the second task comes to the fore: to explain what causes the patterns of continuity and change. New insights into these causes may come when behavioral and functional brain imaging experiments are complemented by studies using the structural brain imaging methods described in this issue. The advent of non-invasive structural neuroimaging methods such as MRI and DTI show special promise as they come to be used in conjunction with behavioral and functional neuroimaging methods, both in studies of normal children and in studies of children with developmental disabilities. By shedding light on the developing morphology and connectivity of the brain, these techniques should help elucidate the mechanisms by which psychological capacities grow and change.

Finally, transcranial magnetic stimulation (TMS) also promises to be a useful tool for studying the causal interactions among developing psychological mechanisms, provided that it proves to be safe for use in children. Following the logic of reversible lesion studies in animals and in human adults, TMS can serve to shed light on the functions of brain regions that are activated during specific behavioral tasks, by charting how both behavioral performance and the neural signatures of cognitive mechanisms are altered when processing in a specific region is temporarily impaired.

In brief, these are exciting times for developmental psychologists. The promise of developmental neuroimaging methods can only be realized, however, if developmental psychologists are able to take on some daunting tasks. First, we need to master a variety of neuroimaging techniques and the principles behind them, so that we can use them intelligently in our research. As part of this task, we need to learn enough physics, biology and mathematics to participate in the interdisciplinary teams that develop and deploy neuroimaging methods. Second, we need to digest the large and explosively growing literature on both structural and functional brain imaging in adults, because this research provides the critical neural signatures of mature psychological processes: the signatures we must use to trace the emergence and development of those processes. Third, we need to rethink training of students in developmental science to prepare them for these promising and challenging new research directions.

As we embrace new fields, however, developmental psychologists should not lose track of the core questions that have guided our field since its inception. These questions do not concern the development of gross brain morphology, or long-range cerebral connectivity, or chemical, molecular or hemodynamic processes, but rather the nature and development of the human mind. As the papers in this special issue attest, studies of neuroanatomy, neurochemistry and neurophysiology are transforming both understanding of normal brain development and diagnosis and treatment of a spectrum of developmental disorders. The full potential of human brain imaging will only be realized, however, when these new techniques are brought to bear on the oldest questions humans have asked about the origins, growth and nature of the human mind.

References

Baillargeon, R. (1999). Young infants' expectations about hidden objects: a reply to three challenges. *Developmental Science*, **2**, 115–132.

Berthier, N., DeBlois, S., Poirier, C.R., Novak, M.A., & Clifton, R.K. (2000). Where's the ball? Two- and three-year-olds reason about unseen events. *Developmental Psychology*, **36**, 394–401.

Caramazza, A. (2000). The organization of conceptual knowledge in the brain. In M. Gazzaniga (Ed.), *The new cognitive neurosciences* (pp. 1037–1046). Cambridge, MA: MIT Press.

Carey, S. (2001). Cognitive foundations of arithmetic: evolution and ontogenesis. *Mind and Language*, **16**, 37–55.

Carey, S., & Xu, F. (2001). Infants' knowledge of objects: beyond object files and object tracking. *Cognition*, **80**, 179–213.

Damasio, A.R. (1990). Category-related recognition deficits as a clue to the neural substrates of knowledge. *Trends in Neuroscience*, **13**, 95–98.

Dehaene, S. (1997). *The number sense*. Oxford: Oxford University Press.

Dehaene, S., Naccache, L., Le Clec, H.G., Koechlin, E., Mueller, M., Dehaene-Lambertz, G., van de Moortele, P.F., & LeBihan, D. (1998). Imaging unconscious semantic priming. *Nature*, **395**, 597–600.

Dehaene, S., Spelke, E., Pinel, P., Stanescu, R., & Tsivkin, S. (1999). Sources of mathematical thinking: behavioral and brain-imaging evidence. *Science*, **284**, 970–974.

Diamond, R., & Carey, S. (1986). Why faces are and are not special: an effect of expertise. *Journal of Experimental Psychology: General*, **115**, 107–117.

Farah, M.J. (1995). A dissociable system for visual recognition: a cognitive neuropsychology approach. In S.M. Kosslyn & D.N. Osherson (Eds.), *Invitation to cognitive science: Visual cognition* (pp. 101–119). Cambridge, MA: MIT Press.

Fuson, K.C. (1988). *Children's counting and concepts of number*. New York: Springer-Verlag.

Haxby, J.V., Gobbini, M.I., Furey, M.L., Ishai, A., Schouten, J.L., & Pietrini, P. (2001). Distributed and overlapping representations of faces and objects in ventral temporal cortex. *Science*, **293**, 2425–2430.

Haxby, J.V., Hoffman, E.A., & Gobbini, M.I. (2000). The distrubuted human neural system for face perception. *Trends in Cognitive Sciences*, **4**, 223–233.

Kanwisher, N. (2000). Domain specificity in face perception. *Nature Neuroscience*, **3**, 759–763.

Kanwisher, N., Downing, P., Epstein, R., & Kourtzi, Z. (2001). Functional neuroimaging of human visual recognition. In R. Cabeza & A. Kingstone (Eds.), *Handbook on functional neuroimaging* (pp. 109–152). Cambridge, MA: MIT Press.

Meck, W.H., & Church, R.M. (1983). A mode control model of counting and timing processes. *Journal of Experimental Psychology: Animal Behavior Processes*, **9**, 320–334.

Piaget, J. (1954). *The construction of reality in the child*. New York: Basic Books.

Pinel, P., Riviere, D., LeBihan, D., & Dehaene, S. (2001). Modulation of parietal activation by semantic distance in a number comparison task. *Neuroimage*, **14**, 1013–1026.

Plaut, D.C. (1995). Double dissociation without modularity: evidence from connectionist neuropsychology. *Journal of Clinical and Experimental Neuropsychology*, **17**, 291–321.

Simon, T.J. (1997). Reconceptualizing the origins of number knowledge: a 'non-numerical account'. *Cognitive Development*, **12**, 349–372.

Spelke, E.S. (1985). Preferential looking methods as tools for the study of cognition in infancy. In G. Gottlieb & N. Krasnegor (Eds.), *Measurement of audition and vision in the first year of postnatal life* (pp. 323–363). Norwood, NJ: Ablex.

Spelke, E.S. (2000). Core knowledge. *American Psychologist*, **55**, 1233–1243.

Tarr, M.J., & Gauthier, I. (2000). FFA: a flexible fusiform area for subordinate-level visual processing automatized by expertise. *Nature Neuroscience*, **3**, 764–769.

Temple, E., & Posner, M.I. (1998). Brain mechanisms of quantity are similar in 5-year-old children and adults. *Proceedings of the National Academy of Sciences*, **95**, 7836–7841.

van Oeffelen, M.P., & Vos, P.G. (1982). A probabilistic model for the discrimination of visual number. *Perception and Psychophysics*, **32**, 163–170.

Warrington, E.K. (1982). The fractionation of arithmetical skills: a single case study. *Quarterly Journal of Experimental Psychology*, **34A**, 31–51.

Wynn, K. (1990). Children's understanding of counting. *Cognition*, **36**, 155–193.

Wynn, K. (1998). Psychological foundations of number: numerical competence in human infants. *Trends in Cognitive Science*, **2**, 296–302.