Educational neuroscience: The early years

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As developmental cognitive neuroscience explores mechanisms of change at the cognitive and neural systems level, a focus is beginning to emerge on the role of educational experiences in shaping the specific functional circuits that give rise to complex cognitive skills such as reading or math. Such studies mark the emergence of educational neuroscience. This interdisciplinary field tackles questions that stretch beyond the normal boundaries of what neuroscience or education research alone can address. In doing so, it pursues insights that are of potential value to the goals of both fields of inquiry. The report by Brem et al. (1) in this issue of PNAS falls squarely within this interdisciplinary area by studying changes in the brain activity of kindergarten children across a series of several functional MRI (fMRI) scans as they engage in different educational activities between each scan.

Reading development has proven to be an early touchstone topic for interdisciplinary work in cognitive development, systems neuroscience, and education. Changes in functional circuitry within and between systems that support vision and language have been linked to progressive cognitive developments in reading ability (2). This research is now beginning to explore the earliest brain-activity changes associated with reading instruction by focusing on how letter-learning activities introduced in kindergarten lead to the emergence of sensitivity to native script.

A repeated-measures fMRI study of kindergarten children (1) shows that, over the course of 8 weeks, accumulating just 3.6 h of playtime with an educational computer program (3) leads to changes in neural activity within regions of the visual system associated with viewing letters (Fig. 1). These changes include increased blood oxygenation level dependent (BOLD) responses in the left occipital temporal cortex and in the scalp recordings of event-related potentials (ERPs) over left inferior posterior electrodes ~250 ms after viewing letter stimuli.

Linking Brain-Activity Changes to Educational Experience

Linking such changes in brain activity to educational experimental manipulations, although important for this field, has proven to be an elusive task (2). Brem et al. (1) enhance the prospects of doing so in several ways. First, they randomly assigned children to one of two educational experiences—the letter–sound Graphogame versus an equally engaging number–math educational game. Second, a crossover phase of the design enabled each group to serve as its own control across the two educational experiences. Third, tracking changes in both fMRI and ERP responses provides converging evidence that the educational manipulation induced change in the processes applied during the online perception of letters. As such, this study marks perhaps the strongest evidence to date linking educational experiences to specific changes in brain activity in young children.

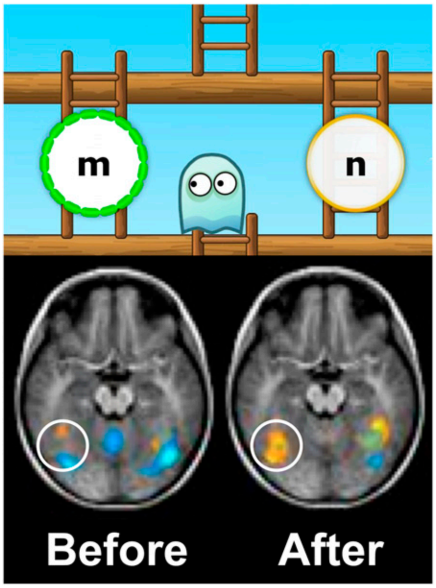

Fig. 1. (*Upper*) Sample stimulus from the Graphogame (3) used to teach kindergarten children letter–speech sound associations. (*Lower*) Axial fMRI results ($z = -10$) contrasting changes in children's activity in left fusiform gyrus in response to letters versus nonletters before and after 3.6 h of training (1).

Remarkably, although these children had real-world experiences with letters before the study, the initial assessment revealed no such letter sensitivity in brain activity, raising interesting issues at the heart of educational neuroscience about why some forms of educationally scaffolded experiences lead to dramatic changes, whereas others apparently lead to little or no change. Was the process of learning to link letters to their corresponding speech sounds a key factor in driving these changes, as the authors suggest? Do these changes merely reflect increased exposure to letters? Such questions are becoming tractable in a way that they were not before as educational neuroscience studies are beginning to contrast different educational approaches to teaching the same content material.

Directly relevant to this point, and perhaps providing further evidence for a rising zeitgeist in support of educational neuroscience, another fMRI study of preschool children published this year (4) contrasted the impact of two educational experiences on occipito-temporal regions associated with recognizing letters. James (4) investigated the hypothesis that the specific educational activities performed with letters, rather than just visual experience with letters, are key factors in driving changes in BOLD responses within the fusiform gyrus. To study this, preschool children were randomized to either a sensori-motor protocol that encouraged them to learn to print letters or a similar condition that encouraged them to name those same letters aloud. This educational contrast, conducted over the course of 1 month, had a profound effect on changes in brain responses to letters. The sensorimotor learning condition produced increases in BOLD responses to letters, especially in the left fusiform gyrus, but it also produced weaker and smaller effects in the right fusiform gyrus. In contrast, children who learned the same letters by naming them aloud showed no changes in these regions. Such findings highlight the potential of educational neuroscience studies to directly examine the critical facets of effective instructional design. As such, this research is beginning to provide insights into how different educational approaches to teaching the same material may impact both learning and changes in functional circuitry that supports such learning.

It may be somewhat surprising that such brief educational interventions lead to changes robust enough to influence children's split-second ERP responses and fMRI responses in left occipito-temporal regions of the visual system. The specific activity measured in these studies (1, 4), however, was derived from activation contrasts between familiarized letters versus nonletters, which offer only minimal constraints on inferences about the level of cognitive change. At a minimum, this

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stimulus contrast may capture a form of sensitivity to script in one's native language, perhaps by temporarily increasing the visual salience of letters relative to novel shapes. Indeed, some aspects of Brem et al.'s crossover results suggest that the educationally induced changes that differentiate letters from other visual stimuli may fade as quickly as they emerge. Yet, the significance of even such a minimal interpretation should not be discounted, because learning to treat the symbols of one's native writing system as highly salient may mark a critical rudimentary step on the long path to establishing specific neural circuits that support reading expertise.

Integrating Neural Systems

Beyond sensitivity to native script, educational neuroscience studies of reading instruction may require investigation of changes across multiple cortical systems. A central example is the ability to fluently associate specific letters with their corresponding speech sounds—a critical component of reading development that is also the focus of considerable debate across educational approaches. Systems-level neuroscience research is well-poised to shed light on educational questions concerning the interaction between multiple neural systems. For example, another study of reading published this year (5) used fMRI to explore the neural basis of third-grade children's emerging sensitivity to the association between particular letters and particular speech sounds. The magnitude of responses in left fusiform gyrus to letters was stronger in typical versus dyslexic readers. Furthermore, fMRI responses in superior temporal brain regions showed a robust sensitivity to audiovisual presentations of letter-sound pairs that were congruently matched versus mismatched, thus capturing sensitivity to the specific associations trained in school and inherent in the children's native writing system. This audio—visual congruency effect was greatly diminished in children with dyslexia, indicating a potential difficulty in integrating these two neural systems. Such insights may hold implications for educational remediation.

Educational manipulation induced change in the processes applied during the online perception of letters.

Educational Computer Games and Educational Neuroscience

As dyslexic children struggle to establish robust cortical associations between visual representations of letters and auditory representations of speech sounds, novel educational innovations may support such learning efforts. Interestingly, the Graphogame used in the Brem et al. (1) study was designed specifically for this purpose (3), and it contains several innovations that are inherent to many such computerized learning approaches.

Each activity in this game was designed to direct a child's attention and decision-making efforts to the specific association between a letter and its corresponding sound. Online algorithms analyze a child's performance and rewrite the lesson plans on the fly depending on which specific confusions the learner shows. Furthermore, the difficulty of the content is adjusted so that the challenges are hard enough to make the learning engaging but not so hard as to lead to frustration. The algorithmic and fully specifiable nature of such programs opens up possibilities for increasingly specific collaborations between education and neuroscience. Guiding design principles of these innovative educational tools today may likely become the subject of neuroimaging studies tomorrow, as this field continues to explore how key factors of effective instruction influence brain plasticity associated with learning (6). Given that adaptive educational computer programs are being developed in tandem with imaging studies of how such innovations drive changes in brain activity, new possibilities may emerge for educational and neuroscience research efforts to inform one another in increasingly rapid cycles.

Considering the larger picture of the emergence of educational neuroscience, it is important to point out that changes in visual responses related to early reading instruction provide but one example of the advances being made by bringing research on education and systems-level neuroscience into closer patterns of interdisciplinary collaboration. The past several years have brought about a virtual explosion of cognitive neuroscience investigations into multiple neural systems that may modulate learning and brain plasticity (6). Attention (7), working memory, social cognition, anxiety (8), motivation, and reward (9) each represent functional domains that have been studied extensively in educational contexts as well as through neuroscience approaches. Combining these approaches via interdisciplinary work opens up opportunities to recast critical educational questions through the lens of developmental cognitive neuroscience. Considering how these neural systems change over the course of learning and development may prove useful for efforts to adapt educational approaches to the unique needs of children who arrive at the doorsteps of formal education exhibiting meaningful differences in the very neural systems on which educational practices must build.

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