Chapter 2

Neuroimaging Tools and the Evolution of Educational Neuroscience

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The key element in the evolution of educational neuroscience was the development of cognitive neuroimaging in the late 1980s. In this chapter, I review the historical record of developments in brain imaging methods such as measurement of changes in blood flow and of electrical and magnetic activity (in both healthy patients and in patients with brain damage). Together, these methods have illuminated the acquisition of literacy, numeracy, expertise, and other aspects of education.

Hemodynamic Imaging

Efforts to image the human brain are ancient, but the modern era began with computerized tomography, or CT scans, which use mathematical algorithms to combine X-rays in such a way as to produce a picture of the brain's structure. However, the images most needed were those showing the brain's *function* during performance of everyday tasks. Efforts to map the function of the brain began by measuring

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blood flow. Using radionucleides that emit photons when in contact with matter, researchers counted the frequency of emissions to map changes in blood flow at various locations in the brain. The major methods used to develop these maps were single photon emission computed tomography (SPECT) and positron emission tomography (PET) (for an extensive history of this field, see Savoy, 2001).

Using PET Imaging

In the late 1980s, it became possible to examine changes in the intact brain while people carried out tasks involving thinking. One method used was called positron emission tomography. PET took advantage of the fact that when brain cells are active, they change their own local blood supply. Using PET, it is possible to show which portions of the brain are active. The PET mapping method was first employed to show how, during tasks such as reading or listening to music, much of the brain, but not the whole brain, exhibited increased blood flow (Lassen, Ingvar, & Skinhoj, 1978). In an important early study, researchers compared specific tasks such as navigating from place to place while reading and listening; the results showed clear regional distribution of brain activity—activity that differed depending on the task (Roland & Friberg, 1985). Prior to the development of functional brain imaging, cognitive psychologists had already broken down tasks such as reading, attention, and visual imagery into component operations or subroutines sufficient to program a computer to perform the tasks (Kosslyn, 1980; Posner & Raichle, 1994). Relating these subroutines to specific brain areas was an important step toward making brain maps useful in psychology and education.

An initial step in connecting subroutines to specific brain areas used PET to examine brain activity while participants listened to and read individual words (Petersen et al., 1988). Participants performed a set of hierarchical tasks (shown in table 2.1) that required looking at a fixed point, reading a word out loud, or generating a use for a word. By "subtracting" the imaging results for each subtask, researchers could roughly isolate the mental operations for each step as participants moved up the hierarchy of increasingly complex tasks.

Table 2.1: Hierarchy of Tasks Designed to Understand the Processing of Single Words and Based on a Theory of Internal Codes in Word Processing (Adapted from Petersen et al., 1988)

Control State	Stimulated State	Areas Activated After Subtraction
Fixation point only	Passive words	Passive word processing
Passive words	Repeat words	Articulatory coding Motor programming and output
Repeat words	Generate uses	Semantic association Selection for action

For example, in the simplest situation, researchers compared the brain activity when participants looked at a screen that showed only a fixation point (this was the control state, shown in the first column of table 2.1) with their brain activity when a single visual or auditory noun was presented at intervals of about a second (the stimulation state, the second column). Subtracting the fixation-only condition from the words provided a measure of where seeing or hearing words activated the brain (the third column, in this case, passive word processing). The visual words strongly activated the visual system and the auditory words the auditory system, thus confirming what would be expected. At the next level, brain activity for the presentation of visual words was subtracted from the activity shown when participants read the same words aloud; thus researchers were able to identify those parts of the brain needed to translate the visual letters into a name and articulate the output. When participants read words aloud, the PET showed major activity in motor areas. At the highest level in table 2.1, participants were asked to generate a use of the presented word: for example, to think of and say a word such as *pound* when presented with the word *hammer*. When they had to produce a use of each noun presented, a brain network was activated that included the left anterior frontal gyrus, the anterior cingulate, parts of the cerebellum, and a posterior temporal-parietal area.

In other words, the highly automated task of reading a word activated one set of areas in the brain, but when subjects had to make a new association with the word, then a different set of areas was activated. During the naming of new associations, it might be concluded, the anterior cingulate was involved in attending to the task, the left frontal area held the input word "in mind," while the posterior area provided the associated meaning. If the same list of words was repeated and participants made the same association, then the strength of the activations decreased. After a few repetitions, producing the association resulted in the same brain activity as simply reading the word aloud (Raichle et al., 1994). Apparently, a few minutes of learning had automated the associations, and they were made more reliably and faster than when they were novel. The brain pathway functioned as though the association was as directly connected to the image of the word as to the process of reading the word. These findings supported the notion that mental operations occur in separate brain areas and showed how quickly these activations could be changed by practice.

Using Functional Magnetic Resonance Imaging (fMRI)

A major development in 1990 was the use of magnetic resonance (MR) to measure localized changes in blood oxygen. PET had required the use of radioactivity to detect blood flow, while MR used no radioactivity—only a high magnetic field—and thus could noninvasively map brain activity (Ogawa et al., 1990). This technology (fMRI) not only was able to reveal much more localized activity than PET, but also had two other features that were very important for cognitive and educational work. First, since fMRI did not use any radioactivity, it could be used with children and to map differences in one individual's brain activity by scanning repetitively. Second, because an individual could be scanned repeatedly without harm, fMRI allowed researchers to combine trials of different types (for example, naming words and generating their uses) within the same series of trials so that participants could not develop a special strategy for each task. Later, the experimenter could average all the word-naming trials separately from the use-generating trials and make the subtraction needed to reveal the networks of brain areas used to generate a simple association.

> A major 1990 development was the fMRI that used no radioactivity, was noninvasive, and could be used with children.

Much subsequent work has confirmed and elaborated the meaning of brain-area activations, particularly with respect to reading.

For example, in a skilled reader, two important posterior brain areas operate automatically: the left fusiform gyrus and the left temporal parietal lobe (see fig. 2.1). The first of these two areas appears to be involved in chunking visual letters into a unit. Often called the *visual word form area* (McCandliss, Cohen, & Dehaene, 2003), it appears to be of special importance in languages that are irregular in pronunciation. English is a particularly irregular language. For example, the "-ave" in *wave* and *have* are pronounced quite differently. While there has been dispute about this area of the brain (Price & Devlin, 2003), most studies have found that it responds to any group of letters that can be pronounced (for example, *iske* is not a word but can be pronounced using the rules of English and would activate the word form area). The second area, the left temporal parietal lobe, is closer to the auditory system and appears to represent the sound of the word. These two areas operate automatically in skilled readers but did not seem to work well in children having difficulty in learning to read (Shaywitz, 2003).

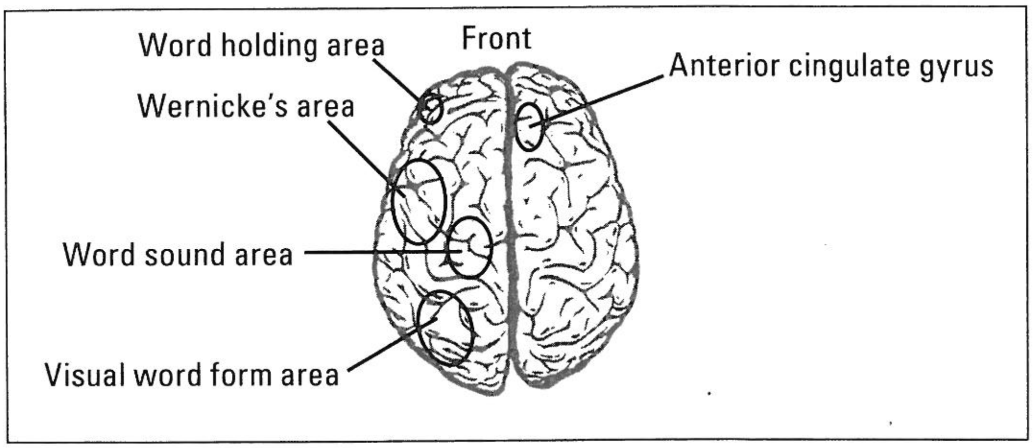

Figure 2.1: Brain areas involved in reading.

These two posterior areas operate in coordination with areas involved in (1) giving effort or attention to the printed word and (2) understanding sentences and longer passages. The anterior cingulate gyrus is a major structure in the executive attention system and is important for regulating other brain networks, including those involved in reading. It operates in conjunction with a left lateral frontal area to hold words in mind while lexical meanings are retrieved from Wernicke's area and from the other highly distributed areas that deal with meaning. Understanding the connotation of a word may also involve information stored in sensory and motor areas.

Use of fMRI has allowed the study of many brain networks not only related to cognitive processes, such as reading, listening, imaging, and so forth, but also to emotional, social, and personality-related processes. A partial list of these networks is shown in table 2.2.

Table 2.2: Some Neural Networks Studied by Neuroimaging

Arithmetic
Autobiographical memory
Faces
Fear
Music
Object perception
Reading and listening
Reward
Self-reference
Spatial navigation
Working memory

Connectivity

As the studies of reading and brain activity show, several neural areas must be orchestrated to carry out any task. One approach to investigating this connectivity uses fMRI to study the timeline of activity and the correlations between active areas of the brain. Figure 2.2 illustrates the connectivity of the anterior cingulate during tasks that involve attention, such as reading and listening. This area of the brain has large-scale connectivity to many other brain areas and is ideally situated to exercise executive control over other brain networks (Posner, 2008).

The executive attention network resolves conflict among competing responses. For example, if you are asked to name the color of ink (such as blue) in which the word *red* is written, there is a conflict between the usual reading response and the instructed response to name the ink color. The executive attention network allows us to inhibit the word name while responding to the ink color. The anterior cingulate is part of this executive network. According to Bush, Luu, and Posner (2000), an analysis of a number of conflict tasks shows that the more dorsal, or rear, part of the anterior cingulate is involved in the regulation of cognitive tasks, while the more ventral, or front,

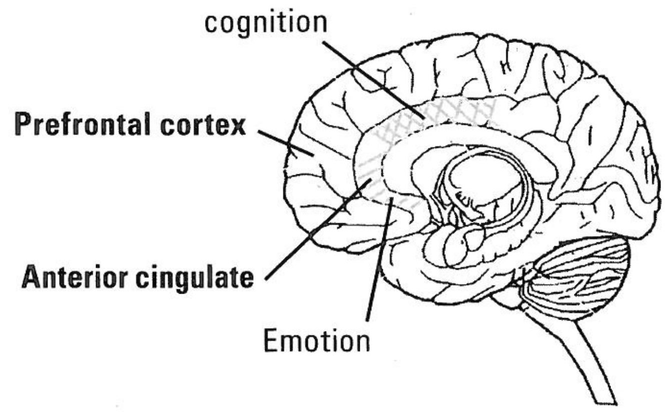

Figure 2.2: The anterior cingulate portion of the prefrontal cortex, shaded in the regions that process emotion and cognition.

part of the cingulate is involved in regulation of emotion. The dorsal part of the anterior cingulate has strong connections to frontal and parietal areas that are also involved in cognitive processes; during task performance, it establishes contact with these brain areas involved in processing information. In one study, for example, participants selected either visual or auditory information in separate blocks of trials. During the selection of visual information, the dorsal cingulate showed correlation with visual brain areas; during the selection of auditory information, it switched, showing correlation to auditory areas (Crottaz-Herbette & Mennon, 2006). In other studies involving emotional stimuli, the more ventral parts of the cingulate became active and became connected to limbic areas related to the emotion being processed (Etkin et al., 2006).

Another approach to measuring connectivity uses noninvasive diffusion tensor imaging (DTI) to reveal the white matter fiber tracts that connect neural areas. This form of imaging measures the diffusion of water molecules in particular directions due to the presence of myelinated fibers (Conturo et al., 1999). Thus it provides a way to examine the physical connections in the brain and trace fiber pathways during different stages of human development.

As noted earlier, because fMRI is noninvasive, it is possible to use multiple scans of the same individual to examine changes that occur with learning and development (Kelly & Garavan, 2005). This obviously is an important tool for educational applications. It is common for learning on a task to decrease the number and extent of cerebral activation. The rate of these changes may vary from milliseconds to years, depending on what is being learned (see table 2.3 for time courses to acquire different kinds of learning). The connectivity of the involved networks also can be enhanced by practice (McNamara et al., 2007). Studies of changes in connectivity as an individual develops show that the local connections dominant in children are supplemented with the longer connections more prominent in adults (Fair et al., 2009). This process is often accompanied by a reduction in the number and extent of activations, as when practicing a given task.

Table 2.3: Time Required to Show Brain Changes Based on Different Causes

Time Course	Cause	Example
Milliseconds	Attention	Conjunctions
Seconds to minutes	Practice	Generation of task
Minutes to days	Learning	New associations
Weeks to months	Rule learning	Orthography
Months to years	Development	Attention system

Electromagnetic Imaging

Because fMRI depends upon changes in blood flow, it develops relatively slowly, and small differences over time may be hard to detect. However, the use of electrical activity recorded from the scalp in the form of the electroencephalogram (EEG) is an old method that can yield high temporal accuracy. Before the development of neuroimaging, it was not possible to tell from an EEG recorded at the scalp where the signal originated in the brain. However, by combining electrical or magnetic recording from outside the head with fMRI, it is possible to get high temporal *and* spatial resolution.

Event-Related Potentials

When a stimulus such as a word is presented many times, the electrical or magnetic activity can be averaged to eliminate the background, not time locked to the stimulus, and form an *event-related potential*. The event-related potential represents the effect of the stimulus on the brain millisecond by millisecond following the stimulus. It is a picture of the brain activity induced by the signal.

For example, Dehaene (1996) used electrical recording from scalp electrodes to map out the time course of mental activity involved in determining whether a number shown visually was above or below five. He used a computer to display a sequence of numbers, which participants had to classify as above or below 5 by pressing a key, then averaged the brain electrical activity following the presentation of each number. During the first hundred milliseconds after the presentation of the input number, the visual system showed activity. When the input was an Arabic numeral (6), both hemispheres were active; when it was a spelled digit (*six*), however, activity was in the visual word form system of the left hemisphere that we described earlier. In the next hundred milliseconds, brain activity varied depending on how close to or far from 5 the number was. This effect of the distance from 5 was shown in the parietal brain areas known to be involved in representing the mental number line. Before the participant pressed the key to indicate above or below 5, electrodes above the motor areas were active. After pressing the key, if the person was in error (for example, had mistakenly indicated that the digit 6 was below 5), activity showed in the frontal midline near the anterior cingulate. Although being able to recognize the quantity of a number is a very elementary aspect of numeracy, training in the appreciation of the value of a number has been shown to be an important contributor to success in learning elementary school arithmetic (Griffin, Case, & Siegler, 1995).

Oscillations

The complex electrical signals coming from scalp electrodes can be separated by analysis into sine and cosine waves. There is a great deal of interest in these oscillations, both in how they show changes of brain state and integration of brain activity in different brain systems. During sleep, for example, deep slow waves predominate; in the awake resting state, created by closing the eyes, alpha frequency (about 10 Hz) dominates, particularly over electrodes at the back of the scalp. When someone realizes he or she has made an error, activity occurs in the theta electrical band (3 Hz) (Berger, Tzur, & Posner, 2006). It has been hypothesized that high-frequency gamma activity (40 Hz) is important in order to tie together distant brain regions that are analyzing a single object (Womelsdorf et al., 2007).

Infants and Young Children

Electrical recordings are sufficiently noninvasive to use with young children, which makes them valuable for understanding what happens in the brain during infancy. For example, infants come into the world already able to discriminate among the units of language (phonemes) in all languages. That is, if an infant hears one phoneme sounded over and over again (for example, *ba*), its novelty effects are reduced. However, a recovery of the novelty effect occurs when the infant discriminates a different phoneme (for example, *da*) from the *ba* that has just been repeated. Thus, the infant exhibits an auditory system that can discriminate between phonemes not only in his native language, but in all of the world's languages. In the period between six and ten months of age, there is considerable shaping of this phonemic structure (Kuhl, 2000). Those sounds to which the infant is exposed tend to solidify and form a unit, while the ability to discriminate unfamiliar sound units begins to disappear. Studies have shown that infants raised in English-speaking homes can maintain their ability to discriminate phonemes in Mandarin Chinese, for instance, if exposed to a speaker of those sounds during this period (Kuhl, Tsao, & Liu, 2003). In addition, phonemes in English (their native language) are also facilitated (Kuhl et al., 2006).

Unfortunately, the studies also revealed that learning did not occur when the language exposure was to a video rather than an actual person. Current research is attempting to determine the most important aspects of these social interactions between an infant and a tutor that facilitate language acquisition in the hope that they could be incorporated into an electronic media presentation. The tutor in these studies used elaborate methods to maintain the interest of the infant, and we simply do not know if these methods can be duplicated by a nonsocial, computer-based system. However, these findings and others like them show that the auditory system of infants is trained by the speech patterns of their community.

learning is a social process

Experiments with infants have also shown that the effectiveness of this training can be measured by variations in the electrical signals that follow a change from a frequent to an infrequent phoneme (Guttorm et al., 2005; Molfese, 2000). As noted earlier, the brain shows its discrimination between the two phonemes by responding differently when the novel phoneme occurs. This electrical difference can be used to measure the efficiency of the brain in making the discrimination. Consequently, we can examine the effectiveness of caregivers in establishing the phonemic structure of their native language and other languages that they desire to teach. From these recordings, it is also possible to predict later difficulties in spoken language and reading (Guttorm et al., 2005; Molfese, 2000). It is still unknown exactly how accurate these predictions can be. Currently, brain stem electrical activity recorded from the scalp allows early detection of deafness in infants. Similarly, use of electrical recording should make it possible to check for the development of a strong phonemic structure even during infancy.

> Brain activity may be measured to help determine the efficiency of a child's language acquisition.

Lesions

Not all parts of an active brain network are needed to carry out a task. In the past, the effects of brain lesions have been studied as a primary way to identify brain areas that, when lost, will prevent a person from performing certain tasks. A good example of the use of lesion data in conjunction with imaging occurred in a study of a patient who had suffered a stroke. He was unable to read words when they were presented to the left of where he was looking (called *fixation*), but he could read them fluently when the words were presented to the right of fixation (Cohen et al., 2004). Imaging revealed an interruption of the neural fibers that conducted information from the right hemisphere occipital lobe (where visual signals are first processed) to the visual word form area (see fig. 2.1, page 31). Typically, the left visual field has direct access to the right hemisphere but must cross over the corpus callosum to access the left hemisphere. In this patient, when words were presented to the left of fixation (that is, presented directly to the right hemisphere of the brain), the patient could only sound them out letter by letter. He demonstrated that he had retained all of his reading skills, however, when words were presented to the right visual field (that is, presented directly to the left hemisphere—the visual word form area). This study illustrates the importance of the visual word form systems for fluent reading.

It is now possible to apply brief magnetic pulses (transcortical magnetic stimulation, or TMS) to the scalp overlying the brain area of interest to disrupt parts of a network at particular times in order to observe the effects on task performance. One striking finding of this technology showed that readers of Braille use the brain's visual system. When TMS was applied to the visual cortex, Braille readers had a specific problem in reading words, suggesting that the visual system was being used to handle spatial aspects of the tactile input from the Braille characters (Pascale-Leone & Hamilton, 2001).

Data from lesion studies may reveal causes of learning difficulties such as dyslexia and dyscalculia.

Lesion data and imaging techniques can be used to confirm and extend theories on learning and brain development. While educators are not usually dealing with patients with specific brain lesions resulting from stroke, findings from these patients can often illuminate specific learning difficulties, such as dyslexia (problems with reading) or dyscalculia (problems with arithmetic).

Genes: Individual Differences in Network Efficiency

Educators are interested in individual differences among students, and this interest has usually involved the study of intelligence(s). Neuroimaging has provided a new perspective on the nature of individual differences. Although most of the networks studied by neuroimaging (see table 2.2, page 32) are common to all people, their efficiency varies, which may be partly due to genetic variations. But the expression of these genetic variations is also influenced by experience. Genes code for different proteins that influence the efficiency with which modulators, such as dopamine, are produced and/or bind to their receptors. These modulators are in turn related to individual differences in the efficiency of one's brain networks.

Humans have much in common in the anatomy of their high-level networks, and this must have a basis within the human genome. The same genes that are related to individual differences are also likely to be important in the development of the networks that are common to all humans. Learning can build on pre-existing brain networks to achieve new functions. For example, primitive appreciation of number is present in infancy. However, when used together with language networks, this primitive sense of numeracy can form a basis for numerical calculation (Dehaene & Cohen, 2007).

In the study of attention, individual differences have been linked to differences in genetic variation. Recall that the executive attention network is involved in the resolution of conflict between other brain systems. The association of the executive attention network with the neuromodulator dopamine is a way of searching for candidate genes that might relate to the efficiency of the network. For example, several studies employing conflict-related tasks found that alternative forms (alleles) of the catechol-o-methyl transferase (COMT) gene were related to the ability to resolve conflict. A number of other dopamine genes have also proven to be related to this form of attention. In addition, research has suggested that genes related to serotonin transmission also influence executive attention (see Posner, Rothbart, & Sheese, 2007, for a review). In studies using brain imaging, it was also possible to show that some of these genetic differences influenced the degree to which the anterior cingulate was activated during the performance of a task. In the future, it may be possible to relate genes to specific points within neural networks, allowing a much more detailed understanding of the origins of brain networks.

While genes are important for common neural networks and individual differences in efficiency, specific experiences also play an important role. Several genes, for instance, including the DRD4 gene and the COMT gene, have been shown to interact with aspects relating to the quality of parenting. For example, one study (Sheese, Voelker, Rothbart, & Posner, 2007) found that in the presence of one version of the DRD4 gene, parents are influential in reducing the impulsivity of their two-year-olds. In children without that version of the gene, however, the quality of parenting did not influence impulsivity. This provides evidence that aspects of the culture in which children are raised can influence the way in which genes shape neural networks—ultimately influencing child behavior (Posner, 2008).

Several genes have been shown to interact with aspects related to the quality of parenting.

If brain networks are affected by parenting and other cultural influences, it should be possible to develop specific training methods to influence underlying brain networks. For example, one study tested the effect of training during the period of major development of executive attention, which takes place between four to seven years of age. Training methods were adopted from primate studies and taught the children to manage conflict. Trained children showed an improvement in conflict resolution skills as well as changes in the underlying brain network—changes that generalized to an IQ test using materials quite different from those involved in the training. Similar studies have shown improvement of attention in classrooms that carry out training in executive function through working-memory training tasks as well as through meditation (see Rothbart et al., 2009, for a review of this work).

Given the wide range of individual differences in the efficiency of attention, it is expected that attention training could be especially beneficial for those children with poorer initial efficiency. These could be children with pathologies that involve attentional networks, children with genetic backgrounds associated with poorer attentional performance, or children raised in various degrees of deprivation.

Summary

Neuroimaging has provided a means of understanding how the human brain operates during tasks similar to those performed in school, such as reading and arithmetic. Networks of brain areas are connected to carry out most tasks of daily life. With practice, the connectivity between brain areas is strengthened, and tasks can be carried out more efficiently. Interrupting networks by temporary or permanent lesions can lead to loss of particular functions. The results of imaging studies have also provided important links between the general networks that are present in all people and the differences in the efficiency of these networks that lead to individuality. Much of the neuroimaging work so far deals with studies common to early education. However, the field is expanding to deal with differences between the expert and the novice brain (Anderson, 2007; Posner, in press). These studies should further expand the usefulness of imaging in secondary and higher education.