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Review of Research: Neuroscience and the Impact of Brain Plasticity on Braille Reading

Cheryl Kamei Hannan

Abstract: In this systematic review of research, the author analyzes studies of neural cortical activation, brain plasticity, and braille reading. The conclusions regarding the brain's plasticity and ability to reorganize are encouraging for individuals with degenerative eye conditions or late-onset blindness because they indicate that the brain can make new connections that have implications for braille reading, tactile perception, and instruction.

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In the field of visual impairments, numerous researchers have studied the intricacies of braille reading, and several books and articles have been written to address the needs of braille readers and teachers of students with visual impairments. The authors have focused on such topics as reading achievement, reading rate, hand movement, hand dominance, tactile perception, learning media, the reading process, assessment, and contracted versus uncontracted literary braille.

Recently, braille reading has gained international attention as medical researchers have revealed groundbreaking studies related to the brain's ability to reorganize itself after the onset of a disability, known as "plasticity." Although these researchers have been interested primarily in neuroscience and medical phenomena, the findings of their studies are relevant to educational practitioners. Contributions from neuroscience have implications for the mechanics of braille reading, tactile perception, and instruction.

In literature reviews, the link between neuroscience and braille has been considered, but the latest medical research on brain plasticity has not been integrated with educational practice. The purpose of this review is to describe the research on brain plasticity and to establish arguments for why this research is relevant to the education of people who are visually impaired (that is, those who are blind or have low vision). By applying a multidisciplinary approach (from medical, psychological, and educational practitioners), this review strengthens the body of research on braille literacy. This research is reviewed after briefly discussing the pathways of the brain involved in reading tasks and brain-scanning techniques used in this research. Finally, the implications for teaching braille reading are presented.

Method

This review of research was conducted using a systematic method. The initial search was conducted in PubMed, a main online index that includes 2,939 journals. The following keywords were used in the preliminary search: *braille, blind, brain plasticity, brain imaging/scanning, neurology, hand dominance, visual cortex, striate cortex, somatosensory, temporal lobe,* and *occipital cortex.* The search produced 50 articles in 34 journals. The articles were further narrowed to those that contained the words *braille* or *blind* and at least one word from the following groups of words: *visual cortex, occipital lobe, striate cortex,* and *primary visual cortex,* or *V1*; *parietal* and *somatosensory*; *transcranial magnetic stimulation (TMS), positron emission tomography (PET),* and *functional magnetic resonance imaging (fMRI)*; *reorganization, plasticity,* and *cross-modality*; and *tactile perception* and *hand dominance*. The final result was 26 articles. Additional information from online resources, professional journals, and books provided background information on the anatomy of the visual pathway, the sensorimotor cortex, brain scans, tactile perception, literacy, and neurology.

Background

The brain is divided into four main lobes, each with specific functions and purposes, as listed in Table 1 and illustrated in Figure 1. When investigating neural activity of individuals who are visually impaired, researchers are interested primarily in how the occipital and parietal lobes function during braille reading tasks. The following section provides anatomical and functional background information about the visual pathway, somatosensory pathway, and how brain activity is measured along each pathway. While reading the article, it may be helpful to refer to Table 2 for related vocabulary.

THE VISUAL PATHWAY

Understanding the physical anatomy and neurology of the visual pathway is essential to understanding research that is related to brain plasticity and tactile reading. Many professionals in the field of visual impairment are familiar with the ocular portion of the visual pathway leading to the retina. The following section focuses on the postretinal visual pathway.

Visual information from the retina travels through the optical tract to the lateral geniculate nucleus (LGN), located in the thalamus (see Figure 2). Each person has two LGNs, one in each hemisphere of the brain, allowing for each eye to communicate with the contralateral, or opposite, hemisphere of the brain (contralateral technically means on the other side of the midline from the part that one is describing). The LGN is the control center for information processing (Neuroscience, 2001; University of Bradford, 2005). It sorts visual information, sent via the optical tract, into three areas: the primary visual cortex (which receives information related to form, color, shape, dimension, and orientation), the superior colliculi (which receives information related to movement), and the pretectal area (which receives information gathered from photoreceptors that help regulate the circadian clock).

All visual information related to form, color, shape, dimension, and orientation are sent to the primary visual cortex (a.k.a. the striate cortex, Brodmann's Area 17, or V1) and then to the secondary visual cortex (a.k.a. V2) or the extrastriate areas. Both the primary and secondary visual cortices are located in the occipital lobe. The secondary visual cortex surrounds V1 and is responsible for interpreting relationships between form and color. Impulses that are not passed on to V2 are redirected to the LGN and eventually to the extrastriate areas. The extrastriate areas, found outside the occipital lobe, are responsible primarily for processing what an object is and where the object is located (Rampura, 2005). The temporal visual cortex uses prior memory and experiences to make sense of shapes, colors, and forms. It determines what the object is. The parietal visual cortex interprets where things are in terms of spatial orientation, movement, and dimension.

The primary visual cortex is a major focus of neurological research, mainly because researchers are interested in determining whether the visual cortex is active in people who do not have visual stimulation. The researchers in the articles included in this review have been able to locate the exact areas within the visual cortex that are used during tactile reading by individuals who are blind. Furthermore, they have provided evidence of the brain's ability to reorganize itself in the event of a visual disability or as people acquire new skills, such as tactile reading.

THE SOMATOSENSORY PATHWAY

Researchers have strived to understand the intricate neurological pathways that are related to tactile processing during braille reading. Tactile processing occurs mainly in the somatosensory cortex (S1) of the brain, found in the left and right hemispheres of the parietal lobe. The somatosensory pathway includes neural transmission via sensory receptor cells accumulating in the spinal cord and terminating at the thalamus in the ventrolateral posterior nucleus (VPL) or the intralaminar nuclei. Information from the VPL continues to the S1 area. In the S1 area, information is sorted and sent to the secondary somatosensory cortex (S2) or to other areas of the brain.

Braille reading involves moving the fingertips over tactile stimuli of raised dots. Because brain-scanning techniques measure all cortical activity, isolating specific areas that are used during movement as opposed to during tactile perception is difficult. Practitioners have attempted to isolate these areas and to determine the exact location of a neural stimulus. Stimuli related to movement are identified by locating the neural activity of the first dorsal minimi (the muscle used for movement of the index finger, usually the reading finger) and the abductor digiti minimi (the muscle used for movement of the pinky, usually used as a control). Other practitioners have attempted to minimize confounding factors by isolating the exact reading finger and restraining movement of the muscles by presenting braille dots in a fashion that does not require motion, or in a passive manner. However, Millar (1997) argued that braille reading requires an "active" scanning movement, as opposed to a passive technique of reading. She suggested that fluent reading and processing occur when the fingers move actively across the words. Therefore, the accuracy of reading may be affected if movement is restricted. Other research factors to consider in the mechanics of reading are the number of fingers used, reading hand, and technique or hand movement.

BRAIN-SCANNING TECHNIQUES

To pinpoint areas of neural activity in the brain, researchers have used various scanning techniques: TMS, PET, and fMRI. With TMS, the participant receives a stimulus, and the researcher observes the neural reaction to the stimulus. This technique has been used to determine the location of individual nerves that are fired during braille reading tasks. PET scans measure radioactivity in the brain and produce images or slices of neural activity. This technique was common in the early 1990s, but was considered invasive because it required injections of radioactive material into a participant (Brain Channels.com, 2004). In the past decade, researchers have used fMRI technology. fMRI scans have shown active areas of the brain by measuring levels of oxygen and taking images in rapid succession (.25 seconds apart). By sequencing several pictures, researchers have shown movement of activity from when the brain is at rest to when specific areas become active. They have illustrated how braille readers process information during reading versus nonreading activities. TMS, PET, and fMRI were the most common techniques used in the studies that I reviewed. Other brain-scanning techniques were used and are discussed as appropriate to individual research studies.

Review of research

PLASTICITY OF THE OCCIPITAL CORTEX

Early researchers who studied the reorganization of the primary visual cortex focused on animals that were deprived of visual stimulation. Hubel (1988) wrote about experiments that he conducted in the 1960s in which he and a colleague, Torsten Wiesel, sewed shut one of the unformed eyes in a newborn kitten or monkey. After 10 weeks, the eye of each animal was unstitched. Hubel provided astounding evidence that only 15% of the cells in the visual cortex responded to stimulus presented to the blinded eye, as compared to a normal functioning eye, in which 50% of the cells respond to stimulus. After examining the histology of the primary visual cortex, Hubel and Wiesel found shrinkage of cells corresponding to the eye that was covered and an enlargement of cells corresponding to the uncovered eye. Hubel concluded that the visual cortex was plastic, meaning that the cells were able to reorganize or reorient themselves based on the demands of function. The physiological explanation was that the cells that supported the nonworking eye were no longer needed, so the primary visual cortex reorganized itself to support the cells of the unsutured eye. In the concluding chapter of his book, Hubel stated that further research should answer questions such as, "How plastic is the visual cortex?" and "Within what age span can modifications occur?"

Wanet-Defalque et al. (1988, cited in Büchel, 1998) used PET scanning techniques and found that the metabolic activity in the visual cortex was the same in sighted participants and those who were congenitally blind. They concluded that the occipital cortex was being activated even though vision was not the primary stimulant.

Uhl, Franzen, Lindinger, Lang, and Deecke (1991) conducted further research to determine if activity in the visual cortex was task dependent. The experimental group (of 11 persons who were blind from birth or who had become blind within the first year of life) was given the task of reading sentences in braille and random dot patterns using only the left index finger in a left-to-right motion that is commonly used during braille reading. A control group of 17 individuals underwent tactile training to be able to identify words that were embossed in upper-case letters. The results indicated that the tactile reading tasks activated the visual cortex in the experimental group but not in the control group. Uhl et al. concluded that the involvement of the visual cortex in a deprived occipital lobe is dependent on braille reading tasks.

In another study, Uhl, Franzen, Podreka, Steiner, and Deecke (1992) measured cerebral blood flow through a technique called Brain-SPECT (single-photon emission-computed tomography) and provided evidence that activation of the occipital lobe was greater in the group of 7 participants who were blind than in the 13 sighted participants in the control group. The participants in both groups were given the task of reading random nonbraille dot patterns using passive touch (scanning without meaning) or reading braille using active touch (interactively reading the text). These terms differ from Millar's (1997) theory of tactile perception discussed earlier. The authors concluded that the increased blood flow in the occipital cortex was a result of the reorganization of the brain to accommodate for braille reading skills.

These researchers provided convincing evidence to support Hubel's original claim regarding the plasticity of the brain. The evidence they provided presented an optimistic outlook for adults who lose their vision later in life. The researchers implied that an individual's brain will accommodate and restructure itself to compensate for the loss of vision. Presumably, neurological reorganization of the brain will assist in the rehabilitation of a person with late-onset blindness. Researchers continued to investigate the plasticity of the brain and neural function. They strived to pinpoint the nerves and pathways that are involved during braille reading.

NEURAL INVOLVEMENT IN THE VISUAL CORTICES

Sadato et al. (1996) used PET scanning to investigate the role of the primary and secondary visual cortices in people who were blind. The experimental group exhibited activation of areas V1 and V2 during braille discrimination tasks (n = 8), activation of area V2 during tactile nonbraille discrimination tasks (n = 8), and no activation of the primary visual cortex during the nondiscrimination task (n = 6). The sighted participants (n = 10) showed a decrease in the activation of areas V1 and V2 during the nondiscrimination task and a greater decrease during the tactile nonbraille discrimination task. With these results, Sadato et al. concluded that a significant difference existed in the activation of the primary visual cortex during braille reading in the participants who were blind compared to the lack of activation of the primary visual cortex in the sighted participants during similar tactile discrimination tasks. They established the hypothesis that the role of the primary visual cortex for braille readers is to support braille reading activities.

Sadato and Hallett (1999) used fMRI technology to obtain more accurate results than the PET study just mentioned. Although only one participant was included in this study, the evidence allowed Sadato and Hallett to conclude that somatosensory information is processed in the visual cortex. Sadato and Hallett stated that the visual cortex is used to process tactile information during braille reading tasks and that the somatosensory area of the brain (typically used to process information related to tactile perception, language, reading, spatial reasoning, and integrating spatial and visual information) has less activation during these tasks.

Gizewski, Timmann, and Forsting (2004) also used fMRI technology to study neural activity in the brain during braille reading activities with 12 blind and 12 sighted participants. Their primary purpose was to determine if areas other than those attributed to the somatosensory region were activated during tactile sensorimotor activities. They found neural activity related to hand movement, tactile discrimination, and language. With regard to the occipital lobe, tactile discrimination tasks activated the primary visual cortex, whereas nondiscrimination tasks did not. The results supported those of Sadato and Hallett (1999) that braille reading is more than a sensorimotor task. Gizewski et al. indicated that braille reading is a language and tactile discrimination task. They stated that differences in neural activity during language and tactile discrimination tasks must be further investigated.

All these researchers provided convincing evidence that people who have a visual impairment use the primary visual cortex during braille reading tasks. Yet, Hubel's questions--How plastic is the visual cortex? and Within what age span can modifications occur?--remain unanswered.

CONGENITAL BLINDNESS VERSUS ADVENTITIOUS BLINDNESS

Büchel, Price, Frackowiak, and Friston (1998) were among the first neurologists to investigate the differences between people with congenital blindness and those with late-onset (adventitious) blindness. The premise behind their theory was that people with late-onset blindness would have an increased activation in the visual cortex because of prior visual memory and experiences. The tasks included in the study were braille reading activities with words or nonwords and listening to auditory stimuli. The use of PET scanning created images of areas of greater activation in the occipital and parietal lobes in the braille reading tasks than in the auditory tasks; therefore, the authors concluded that braille reading tasks activate the visual cortex and auditory tasks do not. As hypothesized, greater occipital activation was found during braille reading tasks in the three participants with late-onset blindness (mean age of onset of blindness = 18.3 ± 3.8 years) than in the six participants who were congenitally blind, presumably because of visual memory and experiences. No differences were found between the neural activities of the two groups during the auditory tasks.

Burton et al. (2002) used fMRI imaging to show higher levels of activation in the occipital lobes during braille reading activities in nine participants who were congenitally blind than in seven participants who were adventitiously blind (mean age of onset = 12.7 years). These results contradicted those of Büchel et al. (1998). Burton et al. suggested that the occipital cortex is used for encoding tactile or visual orthography and is a necessary region of the brain for reading, regardless of the reading medium--tactile or visual. They found that the participants who were adventitiously blind showed less activation of the occipital cortex and more activation in the area ipsilateral (on the same side as) to the reading hand than did those who were congenitally blind, who showed activation contralateral (on the opposite side as) to the reading hand. The implications of this finding are discussed later in this article in the section entitled, Hemispheric Relationship to the Reading Hand.

In a subsequent article, Burton (2003) addressed the contradictory results of Burton et al. (2002) and Büchel et al. (1998). Using Millar's (1997) theory that braille readers who became blind later in life depend on shape discrimination and orthographic features when reading tactually, Burton argued that activation of the visual cortex in adventitiously blind individuals would be increased in tasks requiring shape discrimination. However, if tasks did not involve visual features (such as shape), then the brain imaging would show no differences in the use of the primary visual cortex. Despite the contradictory results, the authors of both studies agreed that braille readers who are congenitally blind and those who are adventitiously blind both rely on the occipital cortex during reading.

Millar (1991, cited in Millar, 1997) provided evidence that memory is linear, meaning that the ability to hold more information develops with age. She found a relationship between retrieval speed and the capacity of short-term memory. The adults in her study were able to retrieve information quicker than were the children because adults have a larger memory bank and can draw from more experiences. Millar suggested that any exposure to print adds to the base of knowledge. Therefore, sighted people may be able to generalize faster and recognize things quicker. They also have a larger bank of print experiences for the memory to access. Experiences and prior knowledge contribute to the speed of processing.

The difference in neural pathways between individuals who are adventitiously blind and those who are congenitally blind may be caused by the inherent differences between tactile and visual reading. Since the area of the brain that responds to visual stimulus is larger than is the area for tactile stimulus, a smaller capacity for tactile memory may cause a rapid decay of information (Rex et al., 1995). Rex suggested that the rapid decay of tactile memory contributes to the difficulty in learning and retaining braille characters. However, if the brain is able to reorganize itself, then perhaps the processing that occurs in the occipital lobe compensates for the rapid decay of information.

THE AGE FACTOR

In the literature reviewed so far, researchers were able to show that braille reading tasks activate the occipital lobe and that individuals who are congenitally and adventitiously blind vary in where the processing takes place. Sadato, Okada, Honda, and Yonekura (2002) conducted a study to determine if age is a factor in brain plasticity. Using fMRI technology, they found that during tactile letter-discrimination tasks, all the participants who were blind showed activation of the occipital lobe. However, the nine participants who were congenitally blind (age of onset less than 16 years; mean age 43.6 years) activated the primary visual cortex, whereas the six who were adventitiously blind (age of onset greater than 16 years; mean age 44.5 years) did not. A control group of eight sighted participants (mean age 29 years) showed no activation of the occipital lobe and activation of the parietal and frontal lobes. These findings contradicted the findings of Büchel et al. (1998). Sadato et al. (2002) attributed the contradicting data to differences in the control conditions and in the tactile discrimination tasks. They concluded that age is a factor in brain plasticity and that for individuals who are congenitally blind, unlike those who are adventitiously blind, the processing of tactile discrimination takes place in the primary visual cortex. They stated that "the first 16 years of life represent a critical period for a functional shift of V1 (primary visual cortex) from processing visual stimuli to processing tactile stimuli" (p. 389).

In a follow-up study, Sadato, Okada, Kubota, and Yonekura (2004) investigated cortical involvement during tactile discrimination tasks by giving an fMRI to two adults who had recently become blind with retinitis pigmentosa and had not learned braille. A control group of 19 sighted persons was used as a comparison group. Sadato et al. concluded that activation of the occipital lobe is related to the loss of sensory input because of vision loss and was not a learning-dependent task.

The implication of these two studies (Sadato et al., 2002; Sadato et al., 2004) is that age of onset and degree of vision loss affect plasticity of the occipital cortex. In the conclusion, Sadato et al. (2004) stated that further research is needed to investigate cortical plasticity at various stages of vision loss.

In addition, no studies of elderly adults who have lost their vision have been conducted. Therefore, the results of studies involving brain plasticity may not be generalizable to the geriatric population. Further investigation of cortical involvement at various degrees of vision loss and at different ages of onset would be helpful to educators and advocates of braille.

PLASTICITY OF THE SOMATOSENSORY CORTEX

The studies reviewed thus far have been about plasticity of the occipital lobe during braille reading activities. Yet, researchers have identified additional cortical involvement, particularly in the somatosensory region of the brain (Sadato et al., 1998). How much does the brain reorganize itself to accommodate for a tactile reading medium? Do proficient braille readers have superior tactile sensitivity in their fingertips? The authors of the following studies sought to answer questions related to the plasticity of the sensorimotor cortex, thresholds of tactile sensitivity, and the lateralization of cortical activity.

Pascual-Leone and Torres (1993) compared the plasticity of the sensorimotor cortex of 15 proficient braille readers who used braille more than two hours a day and of 15 sighted participants who were unfamiliar with braille. Somatosensory evoked potentials (SEPs) were used to measure the cortical activity and to map the regions of the brain that were being used during braille reading tasks. All the participants were right-handed, and all the braille readers preferred the right hand when reading braille. When compared with the sighted control group, the blind braille readers had a larger sensorimotor representation for the reading finger than for the nonreading fingers. In addition, the researchers showed that the reading hand and brain hemisphere were contralateral. In other words, readers who read with their right hand exhibited stimulus in the left side of the brain. These results were replicated in the study by Burton et al. (2002) discussed previously.

Pascual-Leone and Torres (1993) hypothesized that the brain reorganizes itself to accommodate for the skills that are necessary during braille reading activities and that plasticity is a result of increased sensory input and the use of the somatosensory region of the brain. They stated that one limitation of the study was that it did not control for side-to-side movements that are necessary when reading braille. The sensorimotor area of the brain may have been enlarged because of hand movements. Therefore, Pascual-Leone et al. (1992) conducted another study to differentiate the areas of the brain that are used for movement versus tactile sensation (note that the 1993 study was published before the 1992 study).

Pascual-Leone et al. (1992) researched the ability of the sensory cortex to reorganize itself as a result of the movement required during braille reading. TMS was used to map the cortical areas related to the first dorsal interosseous (FDI--the muscle that is used for movement of the index finger) and the abductor digiti minimi (ADM--the muscle that is used for movement of the pinky). Twenty blind braille readers volunteered for the study. The authors reported that the cortical representation of the ADM was smaller than the cortical area of the FDI and that movement required by the hands during braille reading may account for changes in the motor cortical mapping of the FDI and ADM muscles. Because the FDI was enlarged, other areas of the reading hand and the nonreading hand had a smaller representation in the sensorimotor cortex. Pascual-Leone et al. (1992) concluded that the brain reorganized itself to accommodate for new sensory input. They also noted that if sensory input increased and served an important function, then the use of neural networks would increase and the brain would gain the capacity to accommodate for the new stimulus--in the case of braille reading, the fingers.

In a later study, Pascual-Leone, Wasserman, Sadato, and Hallett (1995) compared the enlarged somatosensory cortex of six braille readers after a full day of reading and after two days of rest. The purpose was to determine if the enlarged area would change in size depending on the amount of braille stimulation that a person received. All the braille readers learned braille before age 13, and they all read for at least six hours a day as braille proofreaders for the Library of Congress. TMS was used to measure the cortical activity represented by the ADM and FDI muscles. Each participant attended four sessions. Two sessions occurred on a Monday after a weekend of minimal braille reading, and two sessions occurred in the evening after a full day of potential reading. To create a control day, the researchers asked the participants not to go to work one of the days and not to tell them which day they chose to stay home. Pascual-Leone et al. (1995) compared the control day with the workday and found that the right FDI was larger on the workday than it was on the control day. Furthermore, there was no significant difference in the FDI on either of the mornings following a weekend of minimal braille reading. All the participants stated that braille reading tasks were more difficult after a weekend with no braille reading. In a special case, one participant went on a nine-week vacation; the enlargement of the somatosensory area was further decreased following the participant's return. The authors explained this experience by providing evidence that the lack of practice and less stimulation in the form of braille reading will cause the motor cortical area of the brain to shrink, although the area quickly reorganizes, as is seen after a full day's work. Nevertheless, this study supports the notion that reading braille every day is helpful for maintaining reading fluency.

Sadato et al. (1998) investigated activation of the occipital and somatosensory cortices during braille reading, specifically the laterality of finger preference to activation of the left and right hemispheres of the parietal lobe. They found that six readers who preferred the right index finger for reading activated the left and right primary somatosensory regions of the brain, regardless of which finger they chose to use. In contrast, two readers who preferred the left finger activated only the right primary somatosensory region, regardless of which finger they chose.

The authors of these studies provided evidence of somatosensory use and further confirmed that tactile reading tasks activate the occipital lobe. They suggested that early literacy experiences are important for cortical development and that practice in braille reading can contribute to maintaining cortical structure and reading fluency.

MISLOCATIONS OF THE TACTILE STIMULUS

The implication of the enlarged somatosensory area of the brain for the use of non-braille-reading fingers is interesting. If the area of the brain that is used for the reading finger is enlarged, what is the impact on the other fingers? Sterr et al. (1998) studied the reorganization of the somatosensory cortex by comparing the sensory thresholds of each finger in braille readers and sighted nonbraille readers. They found a larger representation in the cortex for three three-finger readers than for six one-finger readers and no representation in the five sighted participants in the control group. They also stated that the sensory thresholds were lower in the braille readers than in the sighted readers. The most interesting finding was that the braille readers had more mislocalizations of the tactile stimulus.

In a follow-up study, Sterr, Green, and Elbert (2003) studied mislocations of the tactile stimulus in more detail. They compared the cortical reaction to a stimulus applied to each finger using microfilaments at various pressures to determine if there was a difference in the thresholds of sighted and braille readers. Another purpose was to determine if a difference existed between the control group of sighted participants (n = 10) and the experimental group of blind braille-reading participants (n = 10) when they were asked to identify the correct finger being stimulated. The results indicated that the sighted participants were more accurate than the braille-reading participants in identifying the location of a stimulus in the lower thresholds. In addition, the right reading hand of the braille-reading participants was less accurate than the nonreading hand in locating a stimulus. Seven of the 10 braille-reading participants had errors in identifying the correct finger when touched by a light stimulus on their braille-reading hand. The researchers hypothesized that the plasticity of the enlarged somatosensory cortex in braille readers accounted for the mislocalization of the stimulus.

HEMISPHERIC RELATIONSHIP TO THE READING HAND

Three studies focused on the relationship between the reading hand and the laterality of the brain. Bradshaw, Nettleton, and Spehr (1982) studied the superiority of the left hand and use of the left hemisphere in language-related tasks and compared the hand superiorities of the contralateral (the opposite side) and ipsilateral (the same side) hemispheres during braille reading. Of the 12 participants in the study, 10 were right-handed and 2 were left-handed (on the basis of their answers to a questionnaire). Four conditions of reading words and names were presented: reading with the right hand contralateral to the hemisphere, reading with the right hand ipsilateral to the hemisphere, reading with the left hand contralateral to the hemisphere, and reading with the left hand ipsilateral to the hemisphere. The study found that hand superiority did not exist and that handedness does not have an effect on braille reading.

Benoit-Dubrocard, Liegeois, and Harlay (1997) discovered that the left hand was more accurately used in reading tasks than was the right hand. This study included 17 right-handed participants and 17 left-handed participants, determined on the basis of the Edinburgh test of laterality and handedness (Oldfield, 1971). Benoit-Dubrocard et al. concluded that handedness and the goal of the task matter in determining exploration patterns. What is more important, they concluded that the left-handed readers were more accurate in meaning-matching tasks. They hypothesized that the naming task requires graphophonic and language interpretation that makes the task more difficult.

Harada et al. (2004) investigated the interhemispheric transfer of activation between hand movement and brain activation. The task required the 19 right-handed sighted participants to recognize same and different braille characters. Cortical activation was measured using fMRI technology. The results did not indicate a statistical significance between the accuracy of the right versus the left hand. Harada et al. concluded that activation occurred in the right hemisphere of the parietal, premotor cortices, regardless of the hand. The findings of this study were analogous to those of the study by Sadato et al. (1998).

Implications

The most significant conclusion of these studies is that the brain is plastic. As

Büchel (1998, p. 1194) stated, the "results also have major implications for the future education of visually impaired children who are likely to develop complete blindness." The most challenging task of educators is to integrate what is known about braille reading with what has been discovered in research in neuroscience and experimental psychology.

The fact that the brain can reorganize itself suggests an optimistic outlook for people who are adventitiously blind and for those with degenerative eye conditions. Researchers have provided evidence that new connections can be made in the brain. These new connections are physical changes made by the body after the onset of a visual impairment. Brain plasticity is a physiological phenomenon that provides a person with a built-in strategy to manage the onset of a visual impairment.

Researchers have further stated that the brain will reorganize itself when a person with a visual impairment learns to read braille. The brain will use the occipital cortex to process tactile information. Currently, the receipt of braille instruction is determined by a learning media assessment. In some cases, a teacher of students who are visually impaired teaches braille to those whose visual impairment is degenerative even though these students do not have a significant visual impairment at the time, and the prognosis is unpredictable. Studies have shown that there is greater brain plasticity in people with significant visual loss than in people who are not visually impaired. However, further research is necessary to determine the effects of braille training for people with low vision. Does a difference in plasticity occur during braille instruction of a person who is blind versus a person with low vision? Are educators teaching a task that is inherently different when a person has a significant amount of usable vision than when a person has significant vision loss? Perhaps development is different when one has vision and is learning braille than when one is blind and is dependent on a tactile reading system.

The literature provides evidence that individuals who spent time blindfolded created new neural connections and used their occipital cortex, but that shortly after their blindfolds were removed and their sight returned, the newly formed connections dissipated. The researchers concluded that skills were easily retained, and that plasticity occurred when the participants were reintroduced to the blindfold. Amedi (2005) posed the theory that perhaps the brain is task dependent and that the occipital lobe assists in organizing visual, tactual, auditory and linguistic information. Nonetheless, educators would want to know how long one could go without exposure to braille reading before atrophy of the skill occurs.

Pascual-Leone et al.'s (1995) study of the braille-reading proofreaders from the Library of Congress suggested an interesting answer to this question. Recall that one participant's nine-week vacation negatively affected her braille reading skills, but that after the participant returned, she quickly regained her reading ability, and her neural activity also regenerated. This finding implies that in avid readers, braille reading skills are retained and reacquired when skills are not used. However, this woman read for at least six hours a day. Persons who are acquiring a new skill or who have not rewired their brains will not have the same retention or reacquisition of skills.

Probably the most important impact of this idea is the reinforcement of the old saying, "practice makes perfect!" Applying this saying to what is known about reading, one can say that "the more you read, the better you get at it" (Trelease, 2005). Now, there is neurological evidence that the brain reorganizes itself to accommodate for a tactile reading skill and that the lack of practice or reinforcement of skills causes atrophy. For educators, these findings support extended school-year programs and constant exposure to braille reading for beginning readers.

Another consideration is the delivery model for braille instruction. If neural connections are not long lasting, then the inconsistent or periodic delivery of instruction will negatively affect the retention of skills. A natural consequence of poor attendance or the limited delivery of service could be a lower retention of braille reading skills. Students must continuously use braille and have ongoing instruction, especially during the early stages of braille reading. Although this seems to be a logical conclusion, neural-scientific research has not been conducted to show variances in the retention of braille reading skills. Educators would want to know whether retention is better because the brain is reorganizing, is maintaining plasticity, or is affected by the frequency of braille use.

Evidence provided in this literature review suggests that prior memory has an effect on the use of the primary visual cortex during braille reading. Perhaps memory also has an effect on the rate of retention of braille reading skills. Often, the most differentiating traits of students who are adventitiously and congenitally blind are seen when their experiences with literacy and their verbal or language development are compared. Büchel et al. (1998) hypothesized that individuals who are adventitiously blind would have more activation in the primary visual cortex because of a built-up memory bank of previous experiences. This theory was disproved, and less activation in the primary cortex was found in persons who were adventitiously blind who accessed the extrastriate areas. The language center acts as a warehouse for prior memory and the development of concepts. This finding reinforces the importance of early concept development, vocabulary building, and literacy skills.

With regard to age and plasticity, the implications of research on brain plasticity for age apply to individuals who have degenerative eye conditions or those who are adventitiously blind. The body of research is conclusive for the claim that reorganization of the brain occurs as a result of a visual impairment. Individual neurological restructuring differs as a consequence of age, experience, and prior knowledge. Many factors are considered when assessing a student for braille instruction. Often, the most decisive factors are the emotional acceptance of a visual impairment and the readiness to learn an alternative form of reading. Medical researchers have established anatomical reasons why early braille instruction is crucial. They have concluded that a window of opportunity to create neural connections in the primary visual cortex may be limited by age, thus emphasizing the need for early braille literacy skills. However, medical researchers have also stated that reorganization of the brain occurs at any age. The possibility of the brain restructuring at any age is the most optimistic hope for those with degenerative eye conditions or late-onset blindness.

Finally, in regard to laterality of the hand and hemisphere, Kozel's (1995) review of the literature on hand superiority in braille reading tasks concluded that the left hand is more accurate than the right hand for two reasons. First, in right-handed people, the left hand was more sensitive than the right hand, and second, the language center was contralateral to the reading hand (Ghent, 1961; Heremelin & O'Connor, 1971; Mommers, 1982; Rudel, Denckla, & Spalten, 1974; Segalowitz, 1983; Smith, 1929). On the basis of the evidence presented in this review of research, one can argue that the left hand is superior and more accurate in braille reading tasks. However, the findings of neurological research have yet to support this claim.

The overall conclusions of this review are encouraging, mostly to those who are new braille readers. For these readers, learning the tactile system can seem like a daunting task. However, the results on the brain's ability to reorganize are encouraging. Research has also supported educational practices regarding early literacy experiences, consistent instruction, and frequent braille services. Finally, to integrate neurological development with best educational strategies, educators need to provide rich, meaningful, and numerous opportunities to read.

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Cheryl Kamei Hannan, *doctoral student, Department of Special Education, Rehabilitation, and Psychology, University of Arizona; mailing address: 4521 West Camino de Cielo, Tucson, AZ 85745; e-mail: <cherylkamei@hotmail.com>.*

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