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How the Blind “See” Braille: Lessons From Functional Magnetic Resonance Imaging

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What does the visual cortex of the blind do during Braille reading? This process involves converting simple tactile information into meaningful patterns that have lexical and semantic properties. The perceptual processing of Braille might be mediated by the somatosensory system, whereas visual letter identity is accomplished within the visual system in sighted people. Recent advances in functional neuroimaging techniques, such as functional magnetic resonance imaging, have enabled exploration of the neural substrates of Braille reading. The primary visual cortex of early-onset blind subjects is functionally relevant to Braille reading, suggesting that the brain shows remarkable plasticity that potentially permits the additional processing of tactile information in the visual cortical areas. *NEUROSCIENTIST* 11(6):577–582, 2005. DOI: 10.1177/1073858405277314

KEY WORDS *Braille, Visual cortex, Sensory deafferentation, Occipital activation, Tactile acuity, Neuroimaging*

Independent Sensory Modalities

Visual and tactile information is relayed from the eyes or the skin to the brain along physically separate pathways. At the level of the cerebral cortex, there are separate primary areas that independently process information for vision and touch; these are known as the primary visual cortex (V1) and the primary somatosensory cortex, respectively. Although additional processing, and even the merging of visual and somatosensory information, takes place in higher order cortical areas, such processing is dependent upon the primary cortical areas. A loss of V1 results in blindness but does not cause tactile sensory impairment. Likewise, a loss of the primary somatosensory cortex results in a loss of tactile discrimination, yet vision remains intact. Hence, these two pathways are independent at the earliest stages of cortical processing (Pons 1996).

What Is Braille?

Braille is a well-known tactile substitution for visual letter forms for the blind, which consists of a series of raised dots that can be read with the fingers. Braille symbols are formed within units of space known as Braille cells. A full Braille cell consists of six raised dots

arranged in two parallel columns, each having three dots (Fig. 1). Sixty-three combinations are possible using one or more of these six dots. A single cell can be used to represent a letter of the alphabet, number, punctuation mark, or even a whole word. Braille is not a language; rather, it is a code by which languages such as English or Japanese can be written and read. Although attributed to Louis Braille, this system has its roots in the military field. In the early 19th century, a French soldier, Charles Barbier de la Serre, invented a tactile “night writing” code for sending military messages that could be read on the battlefield without light. The system used 12 raised dots to represent sounds but was too complicated to be of practical use. In 1821, Charles Barbier de la Serre met Louis Braille, who had been blind from the age of four. Louis Braille realized how useful this system of raised dots could be and simplified it from the original 12 dots to just 6. Braille has now become a worldwide standard. It is not only an effective means of communication but also a proven avenue for achieving and enhancing literacy for the blind. Hence, Braille reading is an indispensable skill for the blind.

Behavioral Characteristics of Reading Braille

Braille reading is a complex cognitive process that requires the control of finger movements, the perception of raised dots, pattern recognition, and lexical/semantic processing.

Perception

Although the size of the Braille cell is relatively small (Fig. 1), minimum neurophysiological tactile substrata are necessary for a person to be able to read Braille: the moving two-point discrimination must be less than 4 mm

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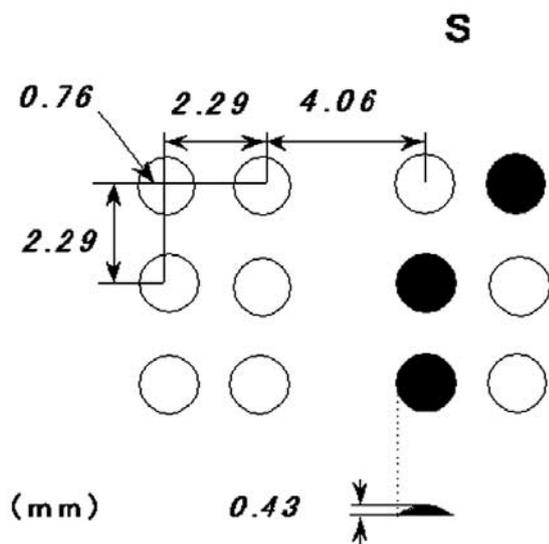


Fig. 1. Design of Braille characters. The Braille characters are composed of the 63 possible combinations of 1 to 6 dots within an array of 6 equally spaced positions, 3 rows and 2 columns, which are called Braille cells. Each cell is assigned to a letter of the alphabet, number, punctuation mark, or composition sign.

and the static two-point discrimination must be less than 5 mm for Japanese Braille to be read (Nakada and Dellon 1989).

Hand Preference

Hand preference is thought to be influenced by multiple confounding factors, such as task demands, length of experience, familiarity with the materials, individual differences in lateralization, reading habits, cultural expectations, and strategy preferences. Reports in the literature reflect the multifaceted characteristics of Braille reading: superior performance has been reported for the left hand (Hermelin and O'Connor 1971; Rudel and others 1974), for the right hand (Fertsch 1947), and for neither hand (Millar 1984). As a left-hand advantage was observed for letter discrimination (and hence, for tactile process) and a right-hand advantage was identified for letter naming (and hence, for lexical process), Millar (1984) suggested that hand advantages depend partly on a combination of task demands and individual strategy preferences. This finding suggests a relationship between verbal processing and hand preference, the details of which are not known.

Effect of Blindness

Does blindness result in enhanced acuity in the remaining senses? There is a long-standing controversy as to whether blind people have enhanced tactile acuity (Axelrod 1959; Warren 1978; Hollins 1989; Pascual-Leone and Torres 1993; Stevens and others 1996; Grant and others 2000; Van Boven and others 2000). Using a fully automated testing system, Goldreich and Kanics

(2003) compared the passive tactile acuity of blind and sighted subjects on a grating orientation task (Johnson and Phillips 1981). Tactile acuity was significantly superior in blind subjects, independent of their degree of childhood vision, light-perception level, or proficiency in Braille reading. Goldreich and Kanics (2003) suggested that cross-modal plasticity might play a role in the enhanced tactile acuity of blind subjects.

Links to Neural Substrates

The behavioral characteristics of Braille reading might be better understood by linking them to their neural substrates. Using functional neuroimaging techniques, such as positron emission tomography (PET) and functional magnetic resonance imaging (fMRI), the neural substrates of these processes have been explored, along with cross-modal plasticity (Box 1).

Neural Substrates of Tactile Shape Discrimination in the Sighted

The neural substrates of tactile shape discrimination are the primary somatosensory cortex and the anterior portion of the intraparietal sulcus in the parietal cortex (Roland and others 1998; Harada and others 2004). Using fMRI, Harada and others (2004) found that, irrespective of the hand used, the right dorsolateral prefrontal cortex, posterior parietal cortex, presupplementary motor area (pre-SMA), and rostral portion of the dorsal premotor cortex (PMdr) were activated asymmetrically during tactile discrimination. This might partly explain the hand preference seen during tactile discrimination of Braille letters by the blind (Millar 1984). No involvement of the visual cortex was observed in the sighted subjects during tactile discrimination (Sadato and others 2002; Harada and others 2004).

Neural Substrates of Braille Reading in the Blind

Tactile Perception

Braille reading involves converting simple tactile information into meaningful patterns that have lexical and semantic properties (Sadato and others 1998). The perceptual processing of Braille might be mediated by the somatosensory system, whereas visual letter identification is usually performed by the visual system. Previous electrophysiological and neuroimaging studies indicated that the visual system of the blind might be used for tactile processing rather than its original purpose (that is, vision). Using [F-18]fluoro-2-deoxyglucose (FDG) PET, Wanet-Defalque and others (1988) showed that the regional cerebral metabolic rate of glucose (rCMRGlc) measured in striate and prestriate areas was as high at rest as during tactile or auditory stimulation. Although they failed to show any task-related increase in neuronal activity, normal MRI results and a high rate of glucose utilization in adult subjects with early blindness of

Box 1: Functional Neuroimaging

Principles of Cerebral Blood Flow

Measurement

Local neural activity, especially synaptic activity, increases in parallel with the glucose metabolism in a particular region of the brain. In turn, regional cerebral blood flow (CBF) parallels the glucose metabolism, which is mediated by the oxygen supply to the region (Raichle 1987). Thus, changes in local neural activity can be inferred by measuring changes in regional CBF. Brain activation studies measure the CBF while a subject executes a particular task compared to that while the subject is relaxed and in a resting state. The distribution of differences in activity between the active and resting states is then visualized. The locations of the activity changes are thought to reflect the regions of the brain that are involved in a particular task.

Historically, positron emission tomography (PET) has been utilized to measure the regional blood flow. This tomographical technique is based on the measurement of gamma rays (emitted when a positron is annihilated) and the calculation of the distribution of the positron-emitting tracer in the body. Using an appropriate tracer, various physiological and biochemical measurements can be conducted in addition to the measurement of CBF.

Recently, another way to measure blood-flow

changes, functional magnetic resonance imaging (fMRI), has frequently been employed. This imaging technique utilizes the nuclear MR of the hydrogen atom. When a hydrogen atom is placed in a uniform static magnetic field, it absorbs (resonance) and emits (relaxation) a radio wave with a specific frequency (nuclear MR). By placing a coil parallel to the static magnetic field, this phenomenon can be detected as a gradually decaying alternating current: the MR signal. The positional information embedded in this MR signal is captured based on the principles of computed tomography. The image obtained primarily reflects differences in the distribution density and the speed of relaxation of the hydrogen atoms, which in turn reflects the different composition of tissues in the body. MRI is suitable for detecting hydrogen atoms, which are present in abundance in the body (primarily as water). For this reason, it is especially useful for imaging neural tissue, which is tightly protected by the cranial bone and the spine. Because of its high-contrast resolution, the initial clinical application of MRI was to image the anatomical details of the brain. At the beginning of the 1990s, however, the visualization of changes in regional CBF was made possible through the use of blood oxygen as an endogenous contrast medium, which paved the way for fMRI (Ogawa and Lee 1990). The advantage of this method is that changes in the CBF to the entire brain can be recorded at intervals of a few seconds, thereby pro-

peripheral origin indicated some functioning of the deprived visual cortex, such as extravisual information processing in the blind. Tactile imagery or Braille reading in blind subjects caused task-related activation in occipital leads using electroencephalography (EEG) (Uhl and others 1991), suggesting that somatosensory input is redirected to the occipital area. Using O-15 water PET, which has better spatial localization than EEG, V1 was shown to be activated when congenitally and early-onset blind subjects read Braille and carried out other tactile discrimination tasks (Sadato and others 1996; Sadato and others 1998), which was confirmed by fMRI studies (Sadato and Hallett 1999; Sadato and others 2002) (Fig. 2). Different neural networks representing different modalities were activated during the performance of tactile discrimination tasks by blind and normal subjects: the tactile processing pathways that are usually linked in the secondary somatosensory area (SII) were less activated in blind subjects than in sighted subjects, whereas the ventral occipital cortical regions that are generally used for visual shape discrimination were more prominently activated in blind subjects (Sadato and others 1998). These findings suggest remarkable brain plasticity, which potentially permits the processing of tactile information in the visual cortical areas.

This plastic change appears to be related to visual deafferentation rather than long-term learning because late-onset blind subjects who were naive to Braille also showed activation in the visual association cortex (Sadato and others 2004). Thus, the neural basis for the improvement in tactile acuity might be due to visual deafferentation (Goldreich and Kanics 2003).

The age dependency of such plastic changes was revealed in a recent fMRI study by Sadato and others (2002): tactile discrimination tasks activated the visual association cortex of both early-onset (<16 years old) and late-onset (>16 years old) blind subjects, whereas V1 was activated only in the former group.

Functional Relevance of V1 Determined by Transcranial Magnetic Stimulation and Lesion Studies

PET and fMRI have revealed the brain networks that are involved in Braille reading in the blind. However, these methods in isolation are insufficient to prove that a certain area is essential for a particular function. Cohen and others (1997) applied repetitive transcranial magnetic stimulation (rTMS) to blind and sighted subject groups (Box 2). They found that interference in the tactile per-

Box 2: Transcranial Magnetic Stimulation

Transcranial magnetic stimulation (TMS) is rapidly developing as a powerful noninvasive tool for studying the human brain. A pulsed magnetic field creates current flow in the brain and can temporarily excite or inhibit specific areas; hence, it is essentially electrical stimulation of the cortex. Stimulation is induced by a brief high-current pulse produced in a coil of wire (the magnetic coil), which is placed above the scalp. A magnetic field is produced to induce an electric field perpendicular to the magnetic field. The electric field causes a current to flow in loops parallel to the plane of the coil. Single-pulse TMS, which is a relatively safe procedure, has been used most commonly. High-frequency (1–30 Hz) repetitive TMS has greater effects than single-pulse TMS but also has the potential to cause seizures, even in normal individuals. However, safety guidelines have been now published that should prevent problems with this method in the future (Hallett 2000).

ception of blind, but not sighted, subjects was produced by stimulation of the mid-occipital region. In a follow-up study, Cohen and others (1999) showed that this interference depended on the age of onset of blindness: congenitally or early-onset blind subjects showed increased error rates following TMS stimulation of the mid-occipital area, whereas no such interruption was seen in late-onset blind subjects. A previous neuroimaging study (Sadato and others 2002) showed that V1 of early-onset blind subjects was activated during tactile discrimination, whereas no such dependency on the onset of blindness was found in the association visual cortex. Hence, V1 of early-onset blind subjects appears to be recruited for tactile discrimination processing in a functionally relevant way.

What Is the Pathway Involved?

As to the mechanism by which the tactile activation of V1 might occur, the thalamus is the first level of processing where vision and touch information come together; visual and tactile inputs are completely separated before this stage (for example, retinal projections are physically separated from touch information traveling in the spinal cord). However, even in the thalamus, visual and tactile inputs remain segregated. Hence, the activation of V1 by tactile stimuli is expected to be mediated by cortical mechanisms. Tactile stimulation of the right hand of blind subjects results in the bilateral activation of V1 (Pons 1996; Sadato and others 1996; Sadato and others; 1998; Sadato and others 2002), which cannot be explained by cross-modal reorganization at the thalamic level. This is because only the contralateral side of the body is represented in the thalamus, and the lateral

geniculate nucleus relays inputs only to the cortex of the same hemisphere. Furthermore, tactile activation of V1 was dependent on the age of onset of blindness, but activation of the visual association cortex was not. Thus, V1 is unlikely to be the “entry node” of the cortex for tactile signals that are redirected into visual cortices after visual deprivation. V1 is a topographically organized “low-level” cortex (in the sense that it is involved in an early stage of visual processing), which receives high-resolution information during bottom-up perception, thus enabling effective edge-detection and regional-organizing processes (Felleman and Van Essen 1991). A visual imagery task that requires the visualization of patterns that depict information such as length, width, orientation, and the amount of space between bars was shown to activate V1 in a functionally relevant way (Kosslyn and others 1999). This finding suggests that stored information can evoke visual patterns in relatively low-level visual areas during imagery, thereby promoting shape processing. Because the majority of visual areas in the macaque monkey have reciprocal connections to other visual areas, such that they receive information from the areas to which they send information (Felleman and Van Essen 1991), it is possible that top-down processing during visual imagery is mediated by the visual association cortex.

Although the exact pathways of top-down processing in blind subjects are not yet known, this activity might be mediated through polysensory areas. In sighted subjects, somatosensory and visual inputs converge in the posterior portion of the intraparietal sulcus, which is a known polysensory area (Saito and others 2003). In blind subjects, whose bottom-up visual processing is interrupted, tactile shape discrimination processing might expand into the visual association cortex through the polysensory areas.

This recruitment of the visual association areas might be responsible for the enhancement of tactile acuity in the blind (Goldreich and Kanics 2003). In early-onset, but not late-onset, blind subjects, V1 is also recruited in a functionally relevant way, as in top-down processing during visual imagery, resulting in better performance on shape discrimination tasks in early-onset blind subjects (Sadato and others 2002). Hence, V1 of the blind might be a “high-level” cortex, in other words, one that is engaged late in the processing of tactile stimuli.

Lexical Processing

With regard to lexical processing during Braille reading, Buchel and others (1998) compared cortical activations elicited by word processing in congenitally blind, late-onset blind, and sighted subjects using functional neuroimaging. Despite the different modalities used (visual and tactile), all groups of subjects showed common activation of Brodmann area (BA) 37 by words relative to nonword letter strings. It was concluded that BA 37 is an association area that integrates converging inputs from many regions. Two studies showed occipital activation during auditory verb-generation (Burton and others

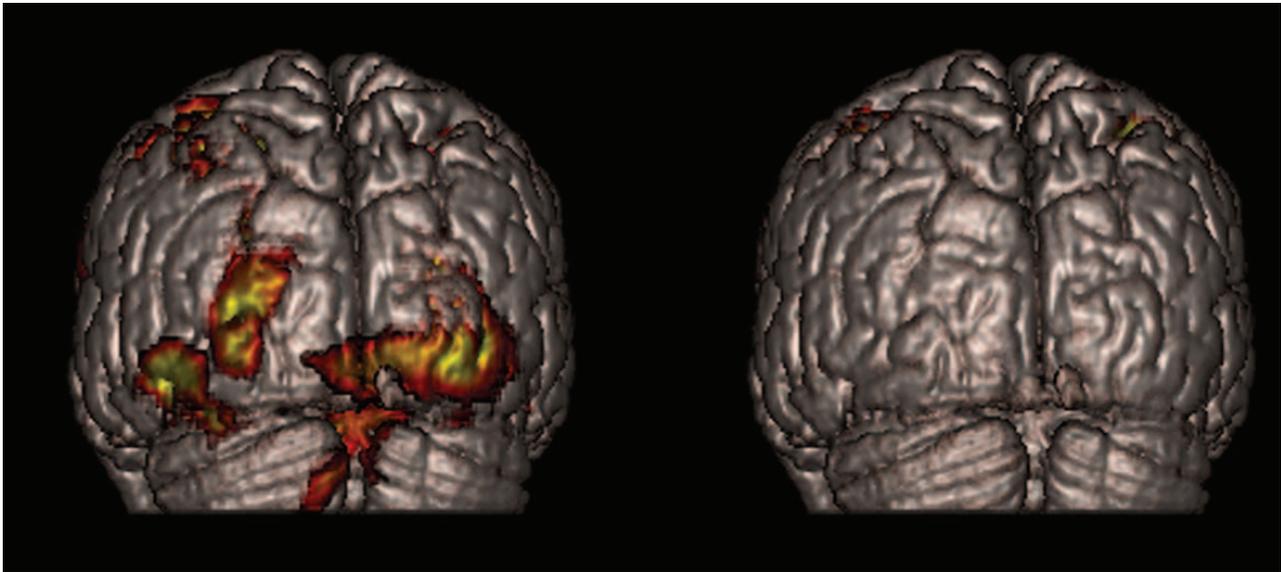


Fig. 2. Areas activated by Braille tactile discrimination tasks in a blind participant who lost his sight at 3 years of age (*left*) and a sighted control (*right*). The brain areas are superimposed on a surface-rendered high-resolution magnetic resonance image viewed from behind. In the blind subject, activity was seen in the occipital lobe, which includes the V1. By contrast, no activation of the occipital lobe was seen in the sighted subject.

2002) and speech-comprehension (Roder and others 2002) tasks, suggesting that the deafferented visual cortex might be engaged in linguistic processing. Amedi and others (2003) assessed fMRI activation in the cortices of congenitally blind subjects during Braille reading, auditory verb-generation tasks, and a verbal-memory task. They found extensive occipital activation in the blind, which involved the V1, during both the verbal-memory and verb-generation tasks. Such activation was not found in sighted subjects. This was reflected in the superior verbal memory abilities of the blind subjects as a group, as well as the strong positive correlation between the blind individual's verbal-memory skills and the magnitude of V1 activation during the verbal-memory epoch. They also found evidence for topographical specialization in the occipital cortices of the blind subjects: anterior regions showed preference for tactile Braille reading, whereas the posterior regions were more active during the verbal-memory and verb-generation tasks. Using rTMS, Amedi and others (2004) confirmed that visual areas are functionally relevant for high-level verbal processing. rTMS of the occipital pole reduced accuracy on a verb-generation task in blind subjects but not in sighted controls. rTMS most commonly produced semantic errors, suggesting that the deafferented visual cortex is involved in lexical processing.

Conclusion

How the Blind "See" Braille: Lessons from Functional Neuroimaging

This report is part of a series of studies on Braille reading by blind people, which has highlighted several

points. Technically, combining complementary electrophysiological and hemodynamic imaging techniques is essential to explore human cortical plasticity. Biologically, marked plastic reorganization of the brain due to sensory deafferentation has been revealed. When V1 is unbound from visual perception, it becomes involved in the processing of other modalities such as tactile discrimination, or amodal processing such as language processing. As this reorganization is probably mediated through the neural networks for tactile-visual cross-modal integration, these findings also shed light on the understanding of multisensory integration.

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