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The Cortical Network for Braille Writing in the Blind

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Abstract

Introduction: *Traditionally, multisensory interactions have been studied primarily at the level of 'sensory modalities'. Conversely, fundamental forms of high-order cognition, such as reading and writing, are usually studied in the context of one modality - vision. People without sight, however, use the kinesthetic-based Braille writing, and haptic-based Braille reading. We asked how modality-specific - or supramodal - are the cognitive and motor control mechanisms underlying writing and reading through either the non-visual or visual modalities? While a number of previous functional Magnetic Resonance Imaging (fMRI) studies have investigated the brain networks for Braille reading in the blind, such studies on Braille writing are lacking. Consequently, no comparative network analysis of Braille writing vs. reading exists. Here, we report the first study of Braille writing, and a comparison of the brain organization for Braille writing vs reading.*

Methods*: FMRI was conducted in a Siemens 3T Trio scanner. Our custom MRI-compatible drawing/writing tablet was further modified to provide for Braille reading and writing. Each of five paragraphs of novel Braille text describing objects, faces and navigation sequences was read, then reproduced twice by Braille writing from memory, then read a second time (20s/task).*

Results and Conclusions*: During Braille reading, the haptic-sensing of the Braille letters strongly activated not only the early visual area V1 and V2, but more specialized spatial representation areas, such as the classical visual grapheme area and the Exner motor grapheme area. Braille-writing-from-memory, engaged a significantly more extensive network in dorsal motor, somatosensory/kinesthetic,dorsal parietal and prefrontal cortex. However, in contrast to the largely extended V1 activation in drawing-from-memory in the blind after training (Likova, 2012), Braille writing from memory generated focal activation restricted to the most foveal part of V1, presumably reflecting topographically the focal demands of such a "pin-pricking" task.*

The ability for congenitally blind individuals to read and write Braille is crucial to their daily lives. While previous research has investigated the neural networks involved in Braille reading in the blind (Sadato et al., 1996; Buchel, Price, & Friston, 1998; Burton et al., 2002; Price & Devlin, 2003; Reich, Szwed, Cohen, & Amendi, 2011), no prior work has focused on the underlying brain activation for Braille writing. The present study is thus the first investigation of the neural correlates of Braille writing.

Braille writing, when done by hand, is a highly complex task. To write in Braille, one must create small indentations on the reverse side of a sheet of paper, such that when flipped over, the indentations appear as raised dots in the typical 2x3 Braille cell formation. This rotation also means that Braille writing must be done backwards—from right to left—such that the text reads left-to-right when the sheet is turned over. In this way, Braille writing is much more complicated than sighted writing, as it requires an additional mental rotation and working memory component. What are the neural correlates of this complex and demanding task?

In order to better understand representations of Braille in the brain, we can look to the literature on reading and writing in the sighted. Given its complex and dynamic nature, sighted reading has been shown to involve an expansive network of regions throughout the brain, many of which are concentrated in the left hemisphere (Dehaene, 2009; see Figure 1). Early pre-lexical visual processing of the letters occurs in low-level occipito-temporal regions, including the "visual word form area" (Bolger et al., 2005) and the "grapheme area" in the left fusiform gyrus where the form and identity of the letters are assessed, respectively (Beeson et al., 2003). Meaning is then assigned to these letter forms in temporal regions including the left middle temporal gyrus and the left anterior fusiform gyrus, parietal regions including the left angular gyrus, and frontal regions including the left inferior frontal gyrus (IFG; Jobard et al., 2003; Dehaene, 2009). The left IFG, also referred to as "Broca's area," has also been shown to be involved in the production and articulation of speech that occurs during reading. Other areas implicated in production and articulation include the inferior precentral gyrus, the supramarginal gyrus, and the superior temporal gyrus, all in the left hemisphere. Lastly, other parietal regions, including the posterior superior parietal lobule and the inferior parietal sulcus (Dehaene, 2009; Jobard et al., 2003), are recruited during the serial allocation of spatial attention needed while reading.

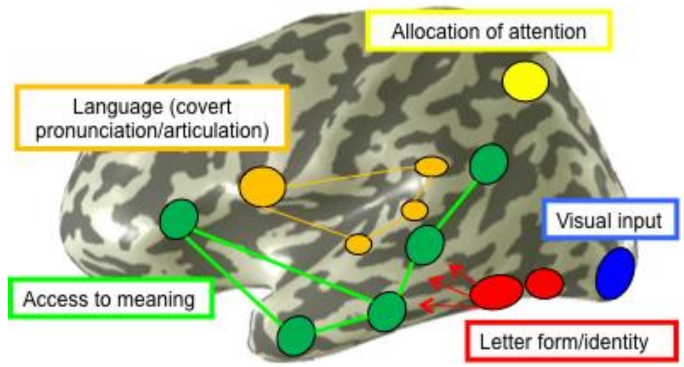

Figure 1: Network for sighted reading. *Image based on Figure 2.2 in Dehaene (2009), with functional attributions of each network keyed by color.*

Previous work has also examined the network involved in reading Braille in those who are blind. In general, the Braille reading network closely resembles the sighted reading network. Interestingly, low-level striate and extrastriate "visual" regions are involved in reading Braille (Burton et al., 2002; Sadato et al., 1996; Buchel, Price, & Friston, 1998; Sathian & Stilla, 2010), even in the absence of visual input. Even the "visual" word form area is active for Braille reading (Price & Devlin, 2003; Reich et al., 2011), indicating that the word/letter form processing that occurs in these occipito-temporal regions is amodal rather than purely visual. Additionally, areas involved in accessing meaning during sighted reading are also involved during Braille reading, including the left middle temporal gyrus, bilateral fusiform gyrus, and the left IFG (Burton et al., 2002). Other frontal areas that have been shown to be active during Braille reading in the blind include the left medial superior frontal gyrus and bilateral precentral sulcus, indicating that Braille reading might involve more extensive recruitment of executive function areas than sighted reading. As in sighted reading, Braille reading also activates parietal regions involved in the allocation of spatial attention, including the left intraparietal sulcus and bilateral superior parietal lobule (Sadato et al., 1996; Burton et al., 2002). Together, this network for Braille reading in the blind mimics the network for reading in the sighted (see Figure 1).

Writing is a highly complex cognitive function that, like reading, requires the recruitment of an extensive cortical network (see Figure 2). Writing in the sighted involves similar early visual areas recruited during reading, including the primary visual cortex and the grapheme area in the posterior fusiform gyrus involved in assigning letter identity (Beeson et al., 2003). As in reading, letter/word meaning must be accessed, but in the case of writing, the access to meaning facilitates the generation of the appropriate letters and words. This semantically-guided generation of orthography involves a network of fronto-temporal regions including the left inferior and dorsolateral prefrontal cortex as well as the left inferior temporal cortex (Beeson et al., 2003). Writing also involves planning in determining the next word, as well as working memory to retain what

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should be written and what has already been written. In this way, *sighted writing* requires a greater recruitment of prefrontal-dependent executive functions than *sighted reading*. Additionally, writing necessarily involves a motor component not needed during reading. The planning and execution of motor movements are functions of the superior premotor and motor cortices. In addition to these areas, a middle frontal region known as Exner's area has been particularly implicated in sighted writing (Roux et al., 2009; Dufor & Rapp, 2013). Specifically, Exner's area has been shown to be involved in the graphemic-motor integration necessary for writing.

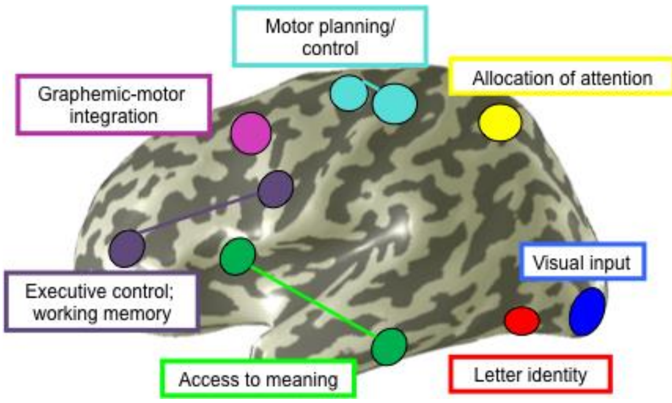


Figure 2: Network for sighted writing. *Areas indicated with their functions are based on Beeson et al. (2003) and Dufor and Rapp (2013), with functional attributions of each network keyed by color.*

Although the above work demonstrates the neural network involved in sighted writing, no previous research has investigated the neural underpinnings of Braille writing in the blind. The present study aimed to provide this important addition to the literature. To do so, we used functional magnetic resonance imaging (fMRI) to assess neural activation during Braille writing in a totally blind participant, MC. While in the scanner, MC used Braille to read meaningful paragraphs describing faces, scenes, and objects, after which he was asked to reproduce those paragraphs from memory via Braille writing. The tools used for Braille writing were MRI-compatible versions of the slate and stylus.

Whole-brain blood oxygen level dependent (BOLD) activation was assessed while MC performed these Braille reading and writing tasks. We predicted that, given the similarities between the reading network for sighted and blind individuals, the writing network in this blind participant would involve similar areas as those involved in sighted writing. Given the motor, memory, planning, and mental rotation components necessary to Braille writing but not to Braille reading, however, we might expect the cortical network involved in Braille writing to be even widespread than in Braille reading.

Methods

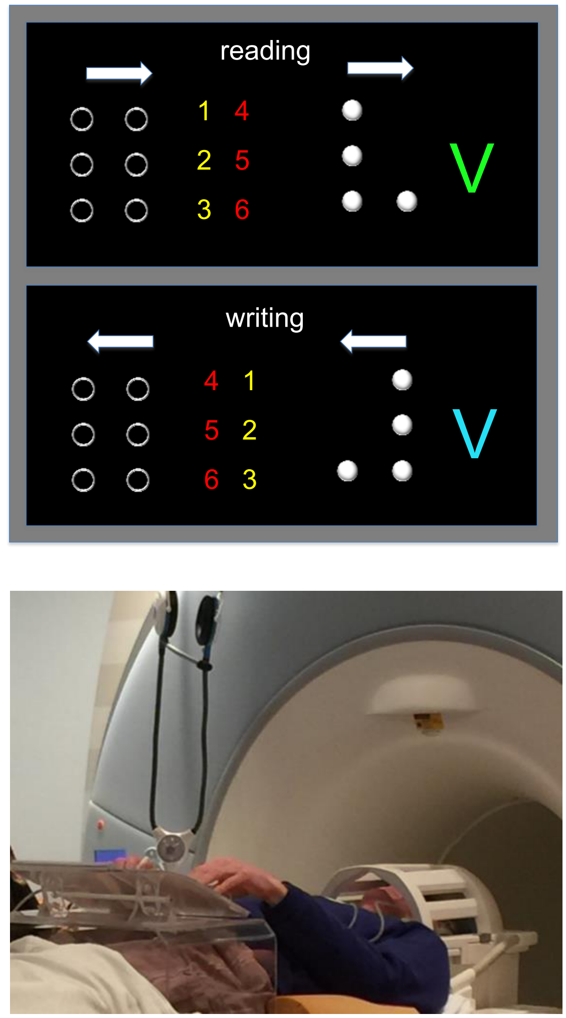
Participant

The completely blind participant, MC, was a 68-year-old right-handed male had no light perception in either eye. His loss of sight was due to retinopathy of prematurity and therefore was never able to use vision to form representations of words or objects based on visual information of any kind. The participant gave informed consent for the experimental protocol, which was approved by the Smith-Kettlewell Institutional Review Board.

MC learned Braille as a child and was considered fluent in both reading Braille and writing with a Braille stylus. He is a sophisticated, highly educated adult who was strongly motivated to participate in the study.

Equipment

Braille writing was accomplished via the use of a slate and stylus system. The slate held the paper on which the participant wrote and consisted of two pieces of plastic held together by a hinge. The back piece was solid with slight indentations for each of the 6 raised dots within each 2x3 Braille cell, and the front piece had rectangular slots corresponding to each Braille cell. The stylus was a blunted aluminum point with a plastic handle.



A

B

***Figure 3. A. Braille reading vs Braille writing**. In Braille reading (upper panel), the raised-dot matrices are read from left to right, as in Western text. The letter V is shown as a specific example. For Braille writing (lower panel) the procedure is mot more complicated. The paper is turned faced down the dots are made from the back of the page, requiring the cells to be punched by the stylus from **right to left** in the form of mirror writing, both within the cells and across the page, so as to be able to read from left to right when flip the paper is inverted for reading. **B. Scanning methodology.** The participant lying with his head in the head coil on the scanner bed about to be slid into the scanner bore, showing our custom plexiglass lectern on which the Braille tablet is mounted for reading and writing during the fMRI scans.*

To use this slate-and-stylus system, a sheet of paper was placed within the slate, and the stylus was used to puncture dots within each Braille cell outlined by the slate to create the desired characters. In the scanner, the MRI-compatible slate and stylus were positioned on top of our custom MRI-compatible lectern (Likova, 2012), providing for both haptic exploration of the Braille text during reading, as well as for Braille writing on a slate through a two-slot (reading/writing) plexiglass table extending across the participant's lap. Auditory cues were presented through Resonance Technologies earphones (Resonance Technologies, Salem, MA).

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Learning how to use slate and stylus of Braille writing is both rewarding and challenging – as one has to learn to write backwards in order to read it properly after flipping the paper to be written on. The blind people have to get used to mirror reversing the letters in their mind, so to be able to read properly what was written when the paper it is flipped. (W. Geary, personal communication)

Design and Procedure

The experiment followed a blocked fMRI design (20 s per activity block). During the "READ" task, the participant read a paragraph of Braille text with his right (dominant) hand. During the "WRITE" tasks, he was instructed to reproduce from memory what he had just read by writing in Braille using the slate and stylus (the stylus being held in his right hand). In order to test memory over time, there were two consecutive writing blocks, "WRITE1" and "WRITE2." The participant performed each task for exactly 20 s, regardless of how much he was able to read or write within that time (i.e., some reading/writing went uncompleted). The tasks were separated by a 20-s rest interval during which the participant was instructed to keep his hands still and clear his mind of any meaningful words or phrases. An auditory cue signaled the beginning of each block. The whole sequence (REST, READ, REST, WRITE1, REST, WRITE2, REST) was repeated for each paragraph of Braille text. There were 5 meaningful paragraphs in total, describing diverse categories (objects, faces, in-door and out-door navigation sequences, and music), while the control 'text' was just randomly created Braille-like characters that did not mean anything. Prior to beginning the pre-training fMRI session, the participant was informed as to the nature of the experiment and briefly familiarized with the tasks and equipment.

Functional MRI Acquisition and Analyses

Data were collected on a Siemens Trio 3T magnet equipped with a 12-channel head coil. BOLD responses were obtained using an EPI acquisition (TR = 2 s, TE = 28 ms, flip angle = 80°, voxel size = 3.0 x 3.0 x 3.5) consisting of 35 axial slices extending across the whole brain. Pre-processing was conducted using FSL (Analysis Group, FMRIB, Oxford, UK) and included slice-time correction and two-phase motion correction, consisting of both within-scan and between-scan 6-parameter rigid-body corrections. To facilitate segmentation and registration, a whole-brain high-resolution T1-weighted anatomical scan was also obtained for each participant (voxel size = 0.8 x 0.8 x 0.8 mm). White matter segmentation in this T1 scan was conducted using FreeSurfer (Martinos Center for Biomedical Imaging, Massachusetts General Hospital) and Gray matter was identified with the mrGray function in the mrVista software package (Stanford Vision and Imaging Science and Technology).

To obtain estimates of neural activation amplitudes for each task, a general linear model (GLM) was fit to the acquired BOLD data for each three-task sequence. The GLM model consisted of a 3 separate 20-s boxcar predictors representing the 3 task activations plus an auditory predictor consisting of sequence of 1-s impulses corresponding to the 6 auditory cues. Each predictor was convolved with an estimated hemodynamic response function (HRF) derived from the whole cortical manifold averaged over the most activated voxels by filtering the 3-cycle sequence at a high activation threshold, and a 4^{th}-order polynomial to account for low-frequency baseline fluctuations. For each task (READ, WRITE), statistical parametric maps (SPMs) were generated based on the estimated activation amplitudes from the above GLM in each voxel that exceeded the noise threshold defined by the variability in the residual. The first WRITE1 epoch was treated as a practice trial, with the analysis focused on the second, practiced WRITE2 epoch.

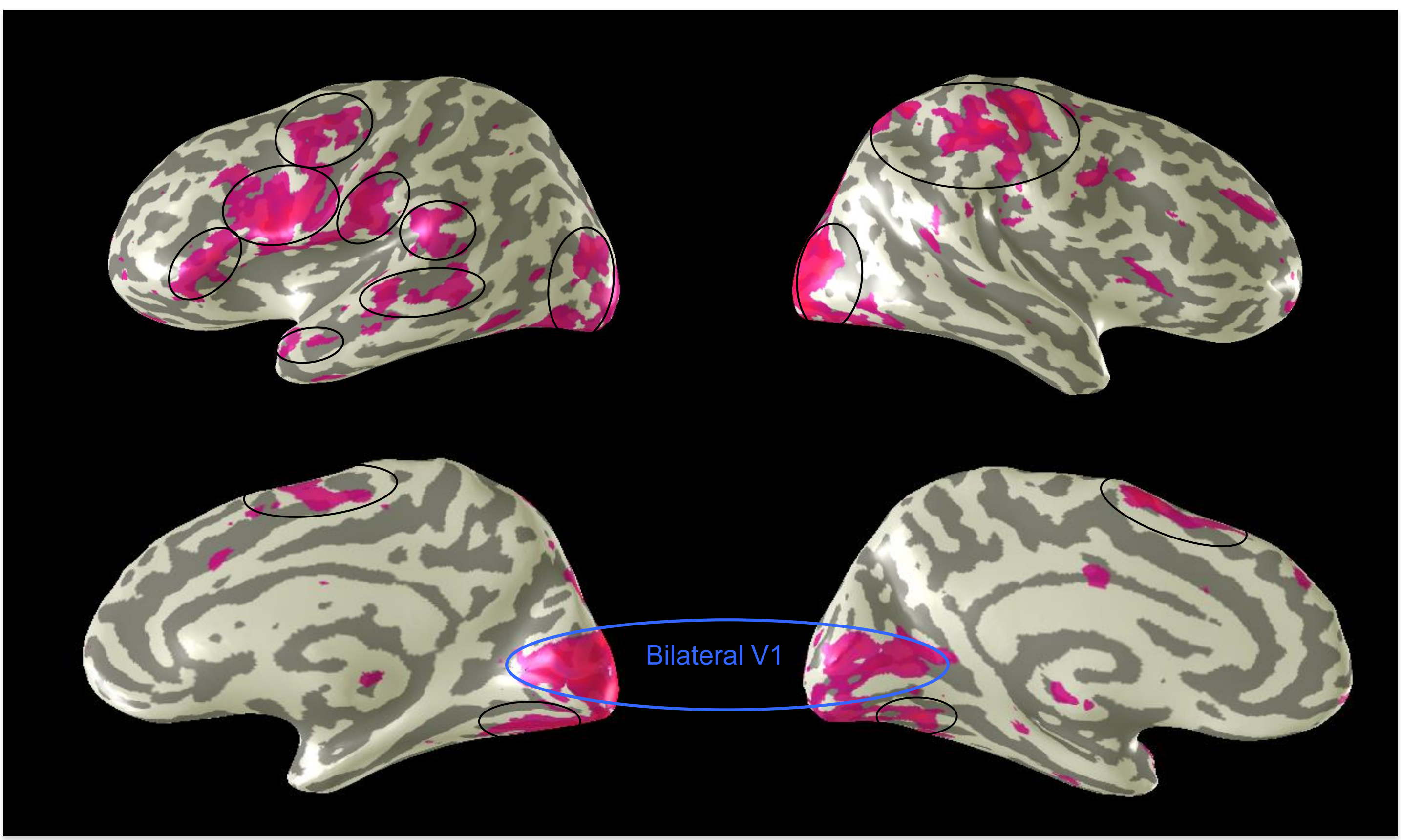

Figure 4. *Cortical regions activated during Braille **reading**, shown on four views of whole-brain inflated cortex. Note strong lateralization of frontal activations and well-structured activation of V1/2 in the brain of this completely blind individual.*

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Results

Braille Reading

The activations for the practiced Braille reading epoch READ2 are shown in Figure 4 in four views of the inflated whole-brain format. Because Braille reading involves finger movements of the left hand, there is the expected activation in the right hand area of the right motor, premotor and somatosensory cortex, together with bilateral supplementary area (SMA) on the dorsomedial surfaces of both hemispheres. Because this is a reading task – although unvocalized - it is also expected that there would be activation in the left superior temporal sulcus (STS), the typical phonological encoding region of the brain (Belin et al., 2000; Dehaene, 2009).

More surprising is the massive occipital activation in this totally blind individual. The posterior medial activation is almost entirely restricted to the region of the bilateral calcarine sulcus and its banks over the lingual (ventrally) and cuneus (dorsally) gyri in the occipital lobe, the sites of visual processing areas V1 and V2. There are also bilateral patches of activation on the lateral surface corresponding to higher areas of the visual hierarchy, as well as on the ventral surface of the occipital lobe corresponding to the visual word form (VFW) or letter identity region. Thus, the occipital cortex in this individual seems to be organized in very much the same way as in a sighted person despite its lack of any visual input throughout his life.

Another unexpected aspect of the reading activation in this individual is the lateralization of the temporal and the frontal lobe activation, which is almost entirely restricted to the left hemisphere (LH). While this might be expected for the Broca area of the inferior frontal gyrus, regions such as the dorsal region of the frontal eye fields (FEF) and the ventral region of the ventrolateral pre-frontal cortex (VLPFC) are usually activated bilaterally (Joliot et al., 2015)., whereas here the activation in these regions is strongly biased to the left hemisphere. This lateralization has been associated with the cognitive control of memory access (Badre & Wagner, 2007). A further site of lateralized activation is the LH anterior temporal pole.

Braille Writing

The brain network activated in Braille writing in the practiced WRITE2 epoch (Figure 5) reveals dramatic differences from the reading activities in several respects, despite the similarities in the tasks and identical information content, with the writing engaging a much more extended brain network. One expected difference is that the motor activations are bilateral, because Braille writing is bimanual, with the right hand controlling the hole-making stylus while the left-hand fingers provide positional information to guide the stylus placement and reading feedback of the holes punched to that point.

Thus, there is an overlap with the core LH-specific activation for reading, although the writing activation is markedly stronger and expanded in the mid-premotor, somatosensory, temporal pole and bilateral SMA regions extending to the most anterior parts of medial surface of the superior frontal gyrus. The bilateral activation, however, extends to pre-frontal areas – which showed minimal activation during reading - notably strong in both lateral and medial pre-frontal regions. Surprisingly, the bilateral occipital activation is markedly reduced, being restricted to what would be the purely *foveal* representation in a sighted individual. Finally, there is a pronounced increase in activation in the RH inferior temporal sulcus, which would be the site of the motion area hMT+ in a sighted individual, implying activation by the sensed motion of the stylus as the Braille letters are punched.

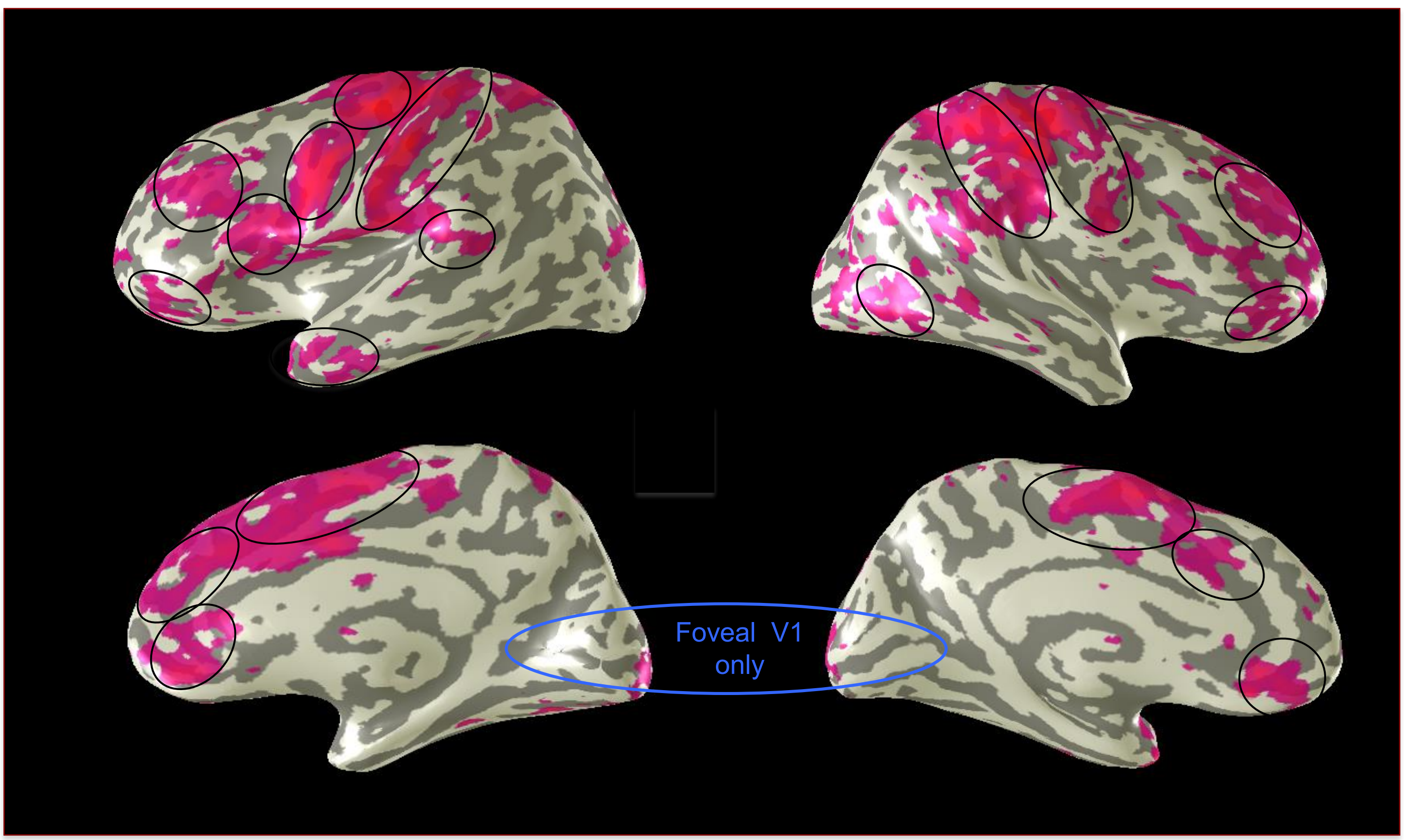

Figure 5. *Cortical regions activated during Braille* ***writing****, shown on four views of whole-brain inflated cortex. Note strong pre-frontal and medial frontal activations and minimal activation of V1/2 in comparison to the reading activation.*

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Discussion

Braille Reading

Before discussing the main results of the Braille writing activation, we consider the Braille reading results, which have similarities to those in previous studies of Braille reading and tactile discrimination in the blind (Sadato et al., 1996; Buchel, Price, & Friston, 1998; Burton et al., 2002; Price & Devlin, 2003; Reich et al., 2011). In particular, the main temporo-frontal network for access to meaning, the lateral occipital areas for spatial word forms and the Broca-Wernicke complex of perisylvian areas for language access and articulation are well activated. One striking similarity to previous studies of Braille reading is the pronounced and well-structured bilateral activation of the early 'visual' cortical areas V1 and V2 seen in Figure 4. Even in this brain which was totally blind from a young age, the primary and subsequent 'visual' cortex regions are strongly activated, supporting the interpretation that they support the supramodal topographic analysis of spatial information from any sensory domain (e.g., Likova, 2012, 2014, 2015).

In addition to this classical reading network, there is a strong left hemisphere (LH) activation in further frontal regions (white ellipse in Figure 6; see also Figure 1). This lateralized activation is unusual because attentional and oculomotor activation of this region is usually bilateral (Joliot et al., 2015). Such activation may represent an extension of the language processing area of the ventral premotor area in this blind individual without the need for oculomotor planning, or it may represent instead a preserved latent form of eye-hand mechanism.

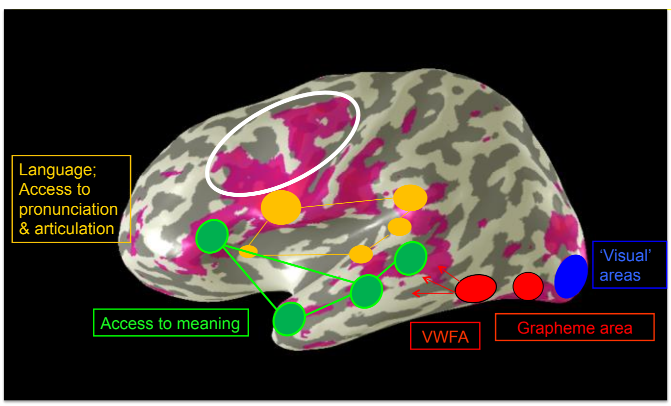

Figure 6. *Average LH lateral activations during Braille reading overlaid with the typical network of reading activations in the sighted from Figure 2, with functional attributions of each network keyed by color.*

Braille Writing

The Braille writing results presented here form the first study of the brain activation network employed during Braille writing, by a blind individual, based on writing from memory with the right hand, while the left hand was supporting the slate and providing a reference for the stylus. Given the increased memory, mental rotation and motor planning components necessary for Braille writing but not for Braille reading, we might expect the cortical network involved in Braille writing to be more widespread than in Braille reading. As predicted, the Braille writing network involves many areas similar to those involved in sighted writing (see Figure 2), including the pre-frontal and right temporal pole areas that are only minimally activated during reading.

Just as in the sighted writing studies of Figure 2, the activation during Braille writing engages a much more dorsal network than for reading and even omits the mid-temporal activation component observed (unilaterally) in the Braille reading. One region, activated in this individual beyond the sighted writing network is the region including the ventral multisensory area of the post-central sulcus, as well as a part of the supramarginal gyrus (white ellipse in Figure 7). This region most likely represents the kinesthetic control required for accurate hand control during writing, although it is unclear why it would be more strongly activated for Braille writing than sighted writing. This activation may be associated with the enhanced activation in the motion area hMT+ in the RH (see Figure 5).

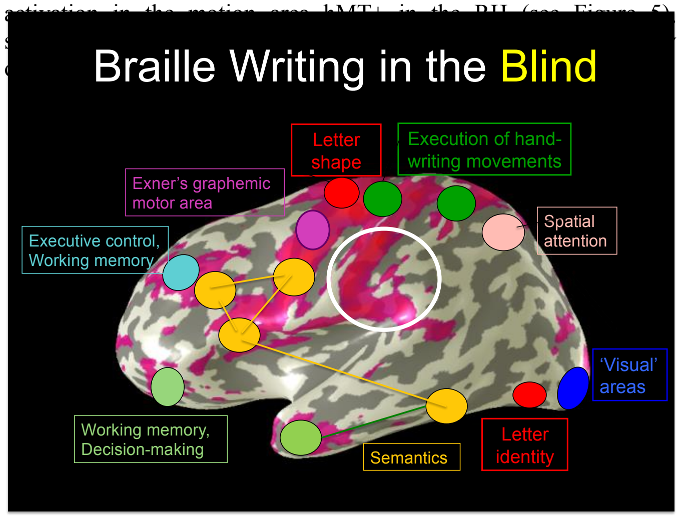

Figure 7. *Average LH lateral activations during Braille writing overlaid with the typical network of writing activations in the sighted, with functional attributions of each network keyed by color.*

Conclusions

This *first study of Braille writing*, together with Braille reading in the same completely blind participant, made it possible not only to develop insights into the writing mechanisms, but also *to compare these two challenging tasks*. Furthermore, comparisons were made between *the haptic (Braille)* and *the visual forms of writing and reading*. During Braille reading, the haptic-sensing of the Braille letters during the reading condition strongly activated not only the early visual areas, but more specialized spatial representation areas, such as the classical visual grapheme area and the Exner motor grapheme area. Braille writing from memory, however, engaged a significantly more extensive network in dorsal motor, somatosensory/kinesthetic, dorsal parietal and pre-frontal cortex, corresponding to attentional and working memory control networks. Nevertheless, in contrast to the largely extended V1 activation in drawing from memory in the blind after training (Likova, 2012), Braille writing from memory generated focal activation restricted to the most foveal part of V1, presumably reflecting the focal demands of such a "pin-pricking" task. Thus Braille writing has an interesting array of both commonalities and contrasts with the range of activations found in blind Braille reading as well as in sighted writing.

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Author Biography

Based on her background in magnetic physics, cognitive neuroscience science and computer science, Dr. Likova has brought together a collaborative team focusing on the enhancement of brain plasticity for the rehabilitation of spatial skills in blind individuals. By replacing the visual eye-hand coordination with memory-hand coordination through an unique Cognitive-Kinesthetic training regimen of less than a week's duration, her lab has been able to achieve major enhancements in both spatial memory and fine spatiomotor skills. Dr. Likova is on the HVEI Organizing Committee.