Effects of Sensory Modality and Experience Deprivation on the Neural Basis of Reading: Evidence from Tactile Braille Reading in Blind Individuals

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Abstract

Perceptual experience deprivation and the acquisition of cultural skills such as reading both induce plastic changes in the brain. Investigating the neural basis of tactile Braille reading in blind individuals provides a unique perspective for understanding this mechanism. This article reviews recent neuroimaging evidence, focusing on three core questions: 1) whether the early visual cortex exhibits reading-specific representations; 2) whether the "visual word form area" in the ventral occipitotemporal cortex retains cross-modal word form processing functions; and 3) whether a "tactile word form area" exists in the parietal lobe. The findings indicate that the functions of the early visual cortex and ventral occipitotemporal cortex remain controversial, whereas the parietal lobe may play a significant role in tactile word form processing. Future research should further elucidate the specific information represented in the "visual" cortex of blind individuals during Braille reading and examine the existence of a "tactile word form area." Simultaneously, it is also necessary to investigate the neural basis of Braille reading proficiency. This will deepen our understanding of brain plasticity mechanisms and provide a theoretical foundation for Braille reading education.

Full Text

The Influence of Sensory Modalities and Experience Deprivation on the Neural Basis of Reading: Evidence from Tactile Braille Reading

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Abstract: Both sensory experience deprivation and the acquisition of cultural skills such as reading can induce plastic changes in the brain. Studying the neural basis of tactile Braille reading in blind individuals provides a unique window into these mechanisms. This review synthesizes recent neuroimaging evidence to address three core questions: (1) whether the early visual cortex exhibits reading-specific representations; (2) whether the "visual word form area" in the ventral occipitotemporal cortex retains cross-modal orthographic processing functions; and (3) whether a "tactile word form area" exists in the parietal cortex. Current findings remain controversial regarding the functions of early visual cortex and ventral occipitotemporal cortex, while the parietal cortex appears to play a significant role in tactile orthographic processing. Future research should further elucidate the specific information represented in the "visual" cortices of blind individuals during Braille reading and test the existence of a tactile word form area. Additionally, the neural basis of individual differences in Braille reading proficiency must be investigated. These efforts will deepen our understanding of brain plasticity mechanisms and provide theoretical foundations for Braille reading education.

Keywords: Braille reading, blindness, neuroplasticity, visual word form area

The human brain exhibits remarkable plasticity, undergoing functional reorganization when faced with sensory deprivation. In congenitally blind individuals, the "visual" cortex activates during non-visual tasks such as tactile and auditory processing (Amedi et al., 2010; Collignon et al., 2011) and participates in numerous higher-order cognitive functions including language processing, Braille reading, and working memory (Bedny et al., 2011; Deen et al., 2015; Kanjlia et al., 2016, 2021; Raz et al., 2005). Conversely, cultural skill acquisition also alters cortical function; for instance, learning to read transforms the ventral occipitotemporal cortex (vOTC), creating a specialized "visual word form area" (VWFA) in the mid-fusiform gyrus for processing written text (Dehaene & Cohen, 2011). What are the principles and mechanisms underlying such plasticity driven by experience or experience deprivation? This question remains central to cognitive neuroscience.

This review examines the neural basis of tactile Braille reading in blind individuals as a model to investigate the mechanisms of experience- and deprivation-induced brain plasticity. Braille is a tactile writing system designed for visually impaired individuals, consisting of raised dot patterns. The basic unit is a "cell" comprising six dots arranged in two columns of three rows. Blind readers process text by sliding their fingers across these dot patterns. While alphabetic Braille systems are based on letters, Chinese Braille is based on pinyin, converting initials, finals, and tones into Braille dot configurations.

In visual reading, visual text information first reaches the primary visual cortex, activating a network that includes early visual cortex, ventral occipitotemporal cortex, temporoparietal junction, and frontotemporal language networks (Figure 1 [Figure 1: see original paper]A), showing remarkable cross-cultural consistency across different languages (Bolger et al., 2005; Rueckl et al., 2015). Reading is a complex process encompassing both language-related processes (phonological and semantic processing) and reading-specific processes (symbol recognition). The VWFA in the mid-fusiform gyrus of the vOTC plays a critical role in visual orthographic recognition (Cohen et al., 2000; Dehaene et al., 2010; Dehaene & Cohen, 2011; Schlaggar & McCandliss, 2007).

Tactile Braille reading, by contrast, begins at the primary somatosensory cortex. Compared to visual reading, Braille reading activates a more extensive neural circuit that includes somatosensory and motor cortices, posterior parietal and dorsal occipital regions, early visual cortex, ventral visual cortex, and frontotemporal language networks (Figure 1B) (Beck et al., 2023; Burton et al., 2002; Cohen et al., 1997; Sadato et al., 1998; Tian et al., 2023). This dual modification—both the sensory entry point and the context of lifelong visual deprivation—provides a unique model for investigating how sensory modality and visual experience deprivation jointly shape cortical functions related to reading. While existing research has mapped the broad cortical regions involved in Braille reading, systematic analysis of these regions' specific roles, interrelationships, and underlying plasticity mechanisms remains lacking. This review organizes evidence from Braille reading studies around mechanistic questions to reveal how different sensory modalities and visual deprivation jointly shape reading-related cortical areas, thereby testing the applicability of task-specific sensory-independent theory and the Cognitively Pluripotent Hypothesis in this domain.

To this end, we focus on three core scientific questions: (1) the functional specificity of early visual cortex in tactile Braille reading—does it merely participate in general tactile processing or higher-level language processing, or does it contain reading-specific representations? (2) Whether the VWFA in the ventral occipitotemporal cortex retains orthographic processing functions in blind individuals, that is, whether a cross-modal orthographic processing mechanism exists. (3) Whether a "tactile word form area" exists in the parietal cortex that is functionally equivalent to the VWFA.

Figure 1. Whole-brain activation maps during visual/tactile reading tasks in sighted (A) and blind (B) participants. The blue dot marks the location of the visual word form area (VWFA) reported in previous literature (MNI coordinate: −46, −53, −20) (McCandliss et al., 2003). The yellow outline marks the location of the hand primary somatosensory/motor area (S1/M1). Adapted from Tian et al. (2023).

2. Functional Specificity of Early Visual Cortex in Tactile Braille Reading

In blind individuals, Braille reading activates early visual cortex, including primary visual cortex (Burton et al., 2002; Cohen et al., 1999; Sadato et al., 1996, 1998; Tian et al., 2023). Transcranial Magnetic Stimulation (TMS) and lesion studies demonstrate that early visual cortex plays a critical role in tactile Braille reading. Stimulation of the dorsal occipital pole produces phosphenes in sighted participants but elicits tactile sensations in the fingertips of early blind individuals, concurrently increasing error rates in Braille letter identification (Ptito et al., 2008). Compared to stimulation of somatosensory cortex, occipital stimulation produces more reading errors and reduces repetition priming effects (Cohen et al., 1997; Kupers et al., 2007). Lesion studies reveal that occipital damage from stroke impairs Braille reading ability (Hamilton et al., 2000). However, these findings only demonstrate involvement of early visual cortex in Braille reading without specifying its precise function or what information it represents.

Some researchers argue that the blind occipital cortex is unlikely to merely subserve low-level tactile sensory functions (Cohen et al., 1997; Sadato et al., 1996, 1998; Tian et al., 2023). Unlike primary somatosensory cortex, occipital activation lateralization does not depend on which hand is used for reading, suggesting distinct functional characteristics between early visual and primary somatosensory cortices (Sadato et al., 1998; Tian et al., 2023). Early visual cortex activates during Braille reading and tactile shape discrimination tasks but not during non-discriminative tactile tasks such as sliding fingers across homogeneous dot surfaces (Sadato et al., 1996), implying that the occipital cortex subserves at least higher-level tactile discrimination functions.

Whether occipital activation is specific to Braille reading remains unresolved. Some studies show that TMS stimulation of occipital cortex increases error rates not only for Braille reading but also for recognizing embossed Roman letters (Cohen et al., 1997). The early visual cortex of blind individuals shows greater activation for non-orthographic tactile discrimination than simple hand movement tasks and exhibits sensitivity to task difficulty (Amedi et al., 2010; Voss et al., 2016), suggesting that early visual cortex may not be Braille-specific but rather supports general tactile stimulus discrimination. However, when early visual cortex is damaged by stroke, patients lose Braille reading ability while other tactile abilities such as object or coin recognition remain intact (Hamilton et al., 2000), indicating the possible existence of Braille-specific functions in the occipital cortex.

Furthermore, some studies have found that early visual cortex, including primary visual cortex, participates in auditory language processing and shows enhanced resting-state functional connectivity with frontal language areas (Abboud & Cohen, 2019; Bedny et al., 2011; Lane et al., 2015). When using Independent Component Analysis (ICA) to identify language networks at rest, congenitally blind individuals show language networks that include lateral occipital cortex (Watkins et al., 2012), and the lateralization of early visual cortex activation during Braille reading correlates more strongly with language network lateralization (Tian et al., 2023). These results suggest that the "visual" cortex of congenitally blind individuals may be integrated into language processing networks. The Cognitively Pluripotent Hypothesis proposes that due to the loss of bottom-up visual input, the visual cortex of blind individuals becomes dominated by top-down remote connections from frontoparietal networks during development, leading it to assume cognitive computational functions different from those in sighted individuals (Bedny, 2017). Thus, an alternative possibility is that early visual cortex activation during Braille reading reflects participation in higher-level language processing rather than tactile shape perception. Previous tactile shape perception studies have also employed naming tasks, confounding language processing with tactile shape processing (Amedi et al., 2010). In summary, early visual cortex may participate in either tactile perceptual processing or higher-level language processing during tactile Braille reading, but current evidence cannot determine whether it contains reading-specific representations.

3. The "Visual Word Form Area" in Ventral Occipitotemporal Cortex: Cross-Modal Orthographic Processing and Language Processing Controversies

A critical region for visual reading is the visual word form area (VWFA) in the mid-fusiform gyrus of the ventral occipitotemporal cortex (Dehaene & Cohen, 2011). Previous fMRI studies have revealed numerous functional properties of the VWFA, including insensitivity to low-level visual features such as word size, retinal position, and letter case; insensitivity to passively presented auditory words; and greater activation for familiar scripts than for unfamiliar languages (Baker et al., 2007; Dehaene et al., 2002, 2004). The VWFA is sensitive to visual orthographic information and sublexical structure, such as letter identity, letter order, and lexical status of short letter strings (Dehaene et al., 2004, 2005; Glezer et al., 2009, 2015), but does not process higher-level language information such as semantics or syntax (Baeck et al., 2015; Fischer-Baum et al., 2017; Kim et al., 2017). Across different writing systems—alphabetic, logographic (e.g., Chinese), or syllabic (e.g., Japanese hiragana and katakana)—reading consistently activates the VWFA (Bolger et al., 2005; Feng et al., 2020; Krafnick et al., 2016; Nakamura et al., 2012; Rueckl et al., 2015). The neuronal recycling theory posits that cultural tools like reading can develop specialized neural mechanisms by "recycling" brain regions originally serving other functions, constrained by existing anatomical and connectional architecture (Dehaene & Cohen, 2007, 2011). From the perspective of intrinsic cortical properties, the VWFA region possesses several characteristics suitable for visual word processing, such as preference for high-resolution foveal input and sensitivity to object shape or part adjacency relationships—the "shape hypothesis" (Hasson et al., 2002; Malach et al., 2002; Szwed et al., 2009, 2011). The biased connectivity hypothesis suggests that the

VWFA occupies an advantageous location with connections to both early visual cortex and frontotemporal language areas (Bouhali et al., 2014; Stevens et al., 2017; Yeatman et al., 2013). These conditions create a favorable "neuronal niche" for word processing that supports the development of a specialized region for recognizing visual text (Dehaene & Cohen, 2007; Hannagan et al., 2015, 2021).

Visual orthographic information is not processed exclusively in the VWFA but rather follows a hierarchical gradient from posterior to anterior regions, with visual word form information entering the brain through primary visual cortex and propagating forward along the ventral visual stream (Vinckier et al., 2007; Zhan et al., 2023). Recent research suggests the existence of two VWFA subregions (Lerma-Usabiaga et al., 2018; Weiner et al., 2017; White et al., 2019). The posterior subregion (pVWFA), located closer to primary visual cortex, is sensitive to smaller processing units such as line features and shows greater activation for letter-based than non-letter stimuli. The more anterior subregion (aVWFA) is sensitive to larger, word-like units and shows greater activation for orthographically legal letter strings than illegal ones (Dehaene et al., 2005; Lerma-Usabiaga et al., 2018; Vinckier et al., 2007). These two subregions also differ in their functional and structural connectivity profiles. Structural connectivity studies indicate that pVWFA may connect to the intraparietal sulcus via the vertical occipital fasciculus, while aVWFA may connect to angular gyrus and inferior frontal gyrus via the arcuate fasciculus (Kubota et al., 2023; Lerma-Usabiaga et al., 2018). Resting-state functional connectivity analyses show that pVWFA has stronger connections with early visual cortex and dorsal occipital and parietal regions, whereas aVWFA shows greater connectivity with frontotemporal language networks (Yablonski et al., 2024).

Numerous studies have found that congenitally blind individuals activate the "VWFA" location during tactile Braille reading (Beck et al., 2023; Buchel, 1998; Dzięgiel-Fivet et al., 2021; Rączy et al., 2019; Reich et al., 2011). Reich et al. (2011) found that Braille words compared to meaningless dot patterns activated a peak in vOTC very close to the classic VWFA. Some studies have also demonstrated orthographic repetition-suppression effects in the VWFA during tactile reading similar to those in visual reading, with no repetition suppression for auditory words, suggesting that the blind "VWFA" is sensitive to sublexical structure of tactile Braille but not to spoken words (Rączy et al., 2019). The task-specific sensory-independent theory posits that after losing bottom-up visual input, the occipital cortex of blind individuals transforms to process information from other sensory modalities while preserving its fundamental cognitive computational functions (Heimler et al., 2015). The blind "VWFA" also shows increased connectivity with frontotemporal language networks, and resting-state functional connectivity patterns in this region are highly similar between blind and sighted individuals (Abboud & Cohen, 2019; Wang et al., 2015). The shape hypothesis suggests that VWFA processing of object shape and part adjacency relationships is modality-independent, so visual text, tactile Braille, and even soundscapes can activate the VWFA, whereas spoken words selectively activate the auditory word form area (AWFA) in the temporal lobe rather than the VWFA (D bska et al., 2023; Hannagan et al., 2015).

However, other studies have found that the blind "VWFA" exhibits functional characteristics different from those in sighted individuals. Similar to early visual cortex, the congenitally blind "VWFA" processes auditorily presented sentences and shows sensitivity to syntactic complexity, contrary to predictions of the shape hypothesis; sighted individuals' VWFA does not process syntactic information (Kim et al., 2017). In visual reading, speech-reading convergence networks across most writing systems are concentrated in perisylvian language regions such as inferior frontal gyrus, middle temporal gyrus, and angular gyrus (Rueckl et al., 2015); however, the blind "VWFA" also shows speech-reading convergence effects, which are absent in sighted individuals' VWFA (Beck et al., 2023; Dzięgiel-Fivet et al., 2021). One study found that congenitally blind individuals' vOTC differs from sighted groups in hierarchical processing: the entire vOTC, extending to primary visual cortex, lacks a hierarchical gradient for orthographic information processing, instead showing overall greater activation for real words than for consonant strings and tactile shape controls (Tian et al., 2023). This study also found bilateral vOTC activation for real word processing, rather than the left lateralization seen in visual reading (Dzięgiel-Fivet et al., 2021; Tian et al., 2023), possibly related to reduced left lateralization of language networks in congenitally blind individuals (Lane et al., 2017). These findings suggest that, similar to early visual cortex, an alternative possibility is that the blind "VWFA" processes higher-level language information rather than tactile orthographic information. Most previous studies have employed designs comparing Braille words to low-level tactile controls such as meaningless dot patterns (Debowska et al., 2016; Dzięgiel-Fivet et al., 2021; Reich et al., 2011), making it impossible to disentangle whether the "VWFA"processes tactile orthographic information or higher-level language information such as phonology or semantics. Although Rączy et al. (2019) used a repetition-suppression paradigm to demonstrate that the "VWFA" shows repetition effects only for tactile Braille and not for auditory language, their tactile task involved detecting specific letters (engaging text processing) while their auditory task involved judging speaker gender (not engaging text processing). This task mismatch prevents direct comparison and cannot rule out the possibility that the blind "VWFA" processes language information.

In summary, two main perspectives exist regarding the function of the ventral occipitotemporal cortex (including VWFA) in blind individuals: the task-specific sensory-independent theory suggests this region retains orthographic processing ability after visual deprivation, merely shifting from visual to cross-modal tactile processing; whereas the Cognitively Pluripotent Hypothesis argues that this region is reassigned to higher-level language processing rather than orthographic analysis after blindness. If the latter is true, tactile orthographic processing must be accomplished by other brain regions (Figure 2 [Figure 2: see original paper]). The parietal cortex deserves special attention in this context, as it plays important roles in tactile spatial information processing and motor control. Could the parietal cortex contain a "tactile word form area" (TWFA) functionally equivalent to the VWFA?

Figure 2. (A) Visual reading network; (B) Hypothesized Braille reading network.

4. The "Tactile Word Form Area" in the Parietal Cortex

Numerous studies have found that Braille reading in blind individuals additionally activates multiple regions in the parietal and dorsal occipital cortices (Burton et al., 2002, 2012; Dzięgiel-Fivet et al., 2021; Sadato et al., 1998). Braille reading originates in the hand sensorimotor areas of the parietal and frontal lobes, with posterior parietal cortex playing a crucial role in tactile shape recognition (Bauer et al., 2015; Hegner et al., 2010). Posterior parietal cortex has dense connections with somatosensory cortex and also maintains connections with frontal language areas and working memory-related regions (Burks et al., 2017; Duhamel et al., 1998; Kaas, 2012; Lewis & Van Essen, 2000; Ruschel et al., 2014). Following the "neuronal niche" logic, posterior parietal cortex possesses favorable conditions for orthographic processing similar to the VWFA—namely, sensitivity to tactile shape recognition and connectivity with language-related regions—making it a candidate location for a "tactile word form area" (Tian et al., 2023). Although no hierarchical processing gradient for visual words was found in congenitally blind vOTC, a hierarchical gradient for tactile words may exist in parietal and dorsal occipital cortices, with anterior parietal regions near primary somatosensory cortex showing greater activation for tactile shapes than text, while posterior parietal and dorsal occipital regions show greater activation for real words (Tian et al., 2023). Another study investigated word length effects in English Braille, which features abbreviations for frequent letter combinations (e.g., "ing" abbreviated as " " , "er" as " "). This study found a region in parietal cortex sensitive to the original word length rather than the abbreviated Braille length, suggesting this region represents sublexical Braille structure rather than low-level perceptual information (Liu et al., 2023).

A recent study used multivoxel pattern analysis and machine learning to dissociate hand-dependent sensory processing from hand-independent perceptual processing in Braille letter reading by having participants read with left and right hands separately. The study found that primary and secondary somatosensory cortices, as well as anterior and posterior intraparietal sulcus, were sensitive to reading hand, whereas early visual cortex and VWFA were not. The authors interpreted hand sensitivity as indicating processing of sensory information about Braille letters, while hand insensitivity suggested higher-level perceptual processing analogous to high-level visual cortex being insensitive to retinal position; lateral occipital cortex fell between these extremes, potentially serving as a transitional zone from sensory to perceptual processing (Haupt et al., 2024). However, Haupt et al.' s findings contradict those of Tian et al. (2023) and Liu et al. (2023), suggesting that parietal cortex only subserves low-level tactile sensory processing. Yet Haupt et al. used single letters that contain no high-level language information, and their conclusion that early visual cortex and VWFA process letters in a hand-independent manner cannot exclude the possibility that these regions process language information. Moreover, in natural reading, blind individuals typically use both hands together, with one hand serving as the dominant reading hand and the other for tracking position or previewing text. Whether hand sensitivity can still serve as evidence for low-level sensory processing given these different functional roles of the two hands in reading remains unclear.

Synthesizing current evidence, parietal cortex participates not only in low-level tactile sensory processing but also likely plays a role in higher-level orthographic information processing during tactile Braille reading. On one hand, some studies have found that posterior parietal cortex is sensitive to Braille sublexical structure and exhibits a hierarchical gradient from perception to orthographic processing, suggesting it possesses the necessary conditions to form a "tactile word form area." On the other hand, other research suggests that parietal cortex primarily subserves low-level sensory processing while higher-level orthographic analysis remains dominated by ventral occipitotemporal cortex. These divergent views reflect inconsistent understanding of the parietal cortex' s localization and function within the Braille reading network. Therefore, whether a functionally equivalent "tactile word form area" exists in parietal cortex represents a critical question requiring clarification.

5. Summary and Outlook

Blind individuals reading tactile Braille activate extensive regions including visual cortices and the VWFA, a key region in visual reading. However, recent research suggests that the congenitally blind "VWFA" processes higher-level language information and may not process tactile orthographic information. Correspondingly, researchers have proposed that a specialized region for processing tactile orthography may exist in posterior parietal cortex—the "tactile word form area." In summary, while current research has broadly outlined the neural circuit for Braille reading in blind individuals, many critical questions remain unresolved.

First, tactile Braille reading in blind individuals activates extensive "visual" regions, including early visual cortex, lateral occipital cortex, and dorsal occipital cortex. However, what information these visual cortices represent during Braille reading remains unclear. One study and our unpublished data indicate that different regions of the blind occipital cortex participate in different higher-order cognitive tasks, including language processing, mathematical processing, long-term memory, and executive control (Abboud & Cohen, 2019). Reading is a complex process encompassing reading-specific processes (symbol identification), language-related processes (phonological and semantic processing), and higher-order cognitive processes such as long-term memory, attention, and executive control. What needs to be clarified is whether the occipital regions activated during Braille reading contain reading-specific areas or instead participate in higher-order cognitive processes related to reading such as language processing or executive control. If reading-specific regions exist, what information do they represent?

Second, it remains unclear whether the "VWFA" still performs tactile orthographic processing in Braille reading. In visual reading research, the VWFA' s reading specificity is supported by multiple lines of evidence, including priming paradigms, multivariate analyses, and longitudinal tracking studies (Baeck et al., 2015; Dehaene-Lambertz et al., 2018; Fischer-Baum et al., 2017; Glezer et al., 2009; Rothlein & Rapp, 2014). In contrast, evidence for VWFA involvement in tactile orthographic processing during Braille reading primarily comes from univariate analyses and comparisons with low-level control conditions, which cannot exclude the possibility that the VWFA processes higher-level language information. Although Rączy et al. (2019) used a priming paradigm to show that the VWFA exhibits repetition suppression only for tactile Braille and not for auditory language conditions, task mismatch prevents direct comparison between conditions.

Third, a promising future research direction concerns whether parietal cortex subserves low-level tactile sensory processing or contains a specialized "tactile word form area." Integrating evidence from Braille reading studies and visual reading research, we propose that Braille reading may involve two or even multiple orthographic processing subregions, similar to visual reading. However, the hierarchical processing gradient in tactile reading likely differs substantially from visual reading. Because the information entry point is primary sensory cortex, the processing pathway from low-level tactile information to higher-level orthographic and language information may not be confined to vOTC but rather constitutes an extensive pathway beginning in parietal cortex and extending to vOTC, lateral occipital cortex, and early visual cortex. Distinguishing what information different regions from parietal to occipital cortex represent during reading may be key to resolving this issue.

Finally, the neural basis of Braille reading proficiency remains largely unexplored. Most research on the neural correlates of Braille reading skill has been conducted in sighted individuals. In sighted adults who learned tactile Braille, activation in Broca' s area, early somatosensory cortex, middle occipital gyrus, inferior occipital gyrus, and ventral visual cortex during reading tasks correlates with reading speed, and resting-state functional connectivity between VWFA and primary somatosensory cortex also correlates significantly with reading speed (Matuszewski et al., 2021; Siuda-Krzywicka et al., 2016). However, the neural basis of Braille reading may differ between sighted and blind individuals. First, Braille reading speeds differ dramatically between these groups. After 8-9 months of tactile Braille training, sighted adults' reading speed only improved from nearly zero (0-1 word/minute) to a maximum of 17 words per minute, averaging 18.41 letters per minute (Matuszewski et al., 2021; Siuda-Krzywicka et al., 2016). In contrast, proficient early blind readers can achieve average speeds of 399 letters per minute (Oshima et al., 2014). Second, visual cortex functional characteristics differ between sighted and blind individuals, and sighted adults have already established mature visual reading networks. These differences may lead to distinct neural substrates for reading. Only a few studies have explored the neural basis of reading speed in blind individuals. One study found that resting-state functional connectivity between left lateral occipital cortex and inferior frontal gyrus correlated significantly with reading speed in late blind individuals (Wang et al., 2024), but did not consider whether participants had learned visual text. Another study (Beck et al., 2023) investigated correlations between brain activation in letter-sound integration regions and reading skills in congenitally blind individuals, but found no significant associations. Some early small-sample studies ($n < 10$) examining differences between congenitally/early blind and late blind individuals yielded inconsistent results. Some found that late blind individuals, like congenitally blind individuals, activate ventral and early visual cortex during Braille reading, albeit to a lesser extent (Buchel, 1998; Burton et al., 2002), while others found that late blind individuals do not activate occipital regions, particularly primary visual cortex, and that TMS stimulation of occipital cortex does not affect their Braille reading performance (Cohen et al., 1999). A study of low-vision individuals found that compared to those who had not learned Braille, those who had learned Braille showed significantly enhanced resting-state functional connectivity between VWFA and postcentral gyrus, reduced connectivity between VWFA and inferior occipital gyrus, with connectivity strength correlating with age of Braille learning onset (Zhou et al., 2020). In alphabetic scripts, late blind individuals read significantly slower than congenitally blind individuals (Oshima et al., 2014), though the reasons remain unclear. Research also suggests that functional reorganization of visual cortex has a critical period (Bedny et al., 2010; Kanjlia et al., 2019; Röder et al., 2021). Clarifying the factors and neural basis of Braille reading proficiency can provide theoretical foundations for Braille reading education.

Future research must first make breakthroughs in task design and processing-level analysis. Current evidence based primarily on univariate analyses and comparisons with low-level control stimuli is insufficient to determine the specific functions of early visual cortex or VWFA in Braille reading. Subsequent studies should employ repetition-suppression paradigms, priming paradigms, and multivariate pattern analysis to distinguish neural representations of low-level tactile processing, orthographic processing, and higher-level language processing. Experimental designs should also account for special characteristics of tactile reading, such as bimanual coordination and reading hand effects, to avoid interpretive biases from task condition mismatches.

Second, in terms of neural mechanism investigation and connectome research, it is necessary to clarify the relationships among parietal cortex, VWFA, and frontotemporal language networks. If a "tactile word form area" exists in parietal cortex, it should exhibit connectivity preferences similar to those of the visual reading network in both functional and structural connections. Future research could combine multimodal imaging techniques (e.g., fMRI, DTI, MEG) to map hierarchical processing pathways from parietal to occipital cortex, elucidating information flow and interaction mechanisms among different brain regions during Braille reading, thereby providing more direct evidence for the debate between task-specific and cognitively pluripotent theories.

Finally, developmental and individual difference studies represent another crucial direction. Longitudinal tracking studies can observe changes in brain function and connectivity before and after Braille learning, establishing causal relationships regarding the role of specific brain regions in reading acquisition. Cross-group comparisons can explore similarities and differences in reading network reorganization among congenitally blind, early blind, and late blind individuals, analyzing how factors such as age of visual onset, age of Braille learning, and visual text learning experience influence the neural basis of reading. Additionally, research should examine neural differences among individuals with varying reading proficiency levels to provide theoretical foundations for Braille education and rehabilitation interventions.

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