

# The Occipital Cortex in the Blind

## Lessons About Plasticity and Vision

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**ABSTRACT**—*Studying the brains of blind individuals provides a unique opportunity to investigate how the brain changes and adapts in response to afferent (input) and efferent (output) demands. We discuss evidence suggesting that regions of the brain normally associated with the processing of visual information undergo remarkable dynamic change in response to blindness. These neuroplastic changes implicate not only processing carried out by the remaining senses but also higher cognitive functions such as language and memory. A strong emphasis is placed on evidence obtained from advanced neuroimaging techniques that allow researchers to identify areas of human brain activity, as well as from lesion approaches (both reversible and irreversible) to address the functional relevance and role of these activated areas. A possible mechanism and conceptual framework for these physiological and behavioral changes is proposed.*

**KEYWORDS**—*plasticity; visual cortex; blindness; Braille reading; verbal memory*

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Conventional wisdom in neuroscience dictates that the brain possesses only limited capacity to reorganize itself following damage (e.g. from sensory loss or brain injury). However, more recent evidence demonstrates that the brain is capable of remarkable dynamic change and adaptation throughout the lifespan. Studying individuals who are peripherally blind (e.g., from eye disease or injury) or using experimental visual deprivation (e.g., prolonged blindfolding) allow researchers to investigate adaptive brain changes and behavioral consequences in response to changes in sensory input. Lessons learned from how the brain adapts to blindness are likely to apply to other situations (e.g., damage to the inner ear) and will provide novel insights for the development of rehabilitative and educational

strategies and the advance of sensory substitution and restoration devices (Merabet, Rizzo, Amedi, Somers, & Pascual-Leone, 2005).

### ADJUSTMENT TO BLINDNESS AND COMPENSATORY PLASTICITY

Blind individuals have to make major adjustments in order to interact effectively with their environment. One might imagine that blind individuals develop superior abilities in the use of their remaining senses in order to compensate for their loss of sight. The accounts of remarkable accomplishments of blind musicians and artists could be taken as anecdotal support for this view. However, blindness has the potential to disrupt brain development and knowledge acquisition, thus ultimately leading to more general problems. For example, because of the strong reliance on vision for the acquisition and construction of spatial and form representations, the loss of sight may have detrimental repercussions on the processing of spatial information that is gathered through the remaining senses. Contradicting the latter view is evidence that blind individuals (as compared with sighted controls) show superior skills in tasks involving touch and hearing (Gougoux, Zatorre, Lassonde, Voss, & Lepore, 2005; Pascual-Leone, Amedi, Fregni, & Merabet, 2005; Rauschecker, 1995; Roder, & Neville, 2003).

The process of seeing is as follows: Focused light landing on the retina causes neuronal signals to leave the eye through the optic nerve; those signals are sent via the lateral geniculate nucleus of the thalamus to the occipital cortex, where the majority of visual processing actually takes place. Sighted people read through visual recognition of words, involving a complex network of language-processing areas intimately related with spatial information processed by the visual system. In contrast, a blind Braille reader relies on touch. Using the pad of the index finger (or multiple fingers for some proficient Braille readers), arrays of raised dots are scanned and spatial information is extracted and interpreted into meaningful patterns that encode semantic and lexical properties. Furthermore, a blind subject also learns to rely on verbal descriptions and verbal memory, in place of visual perception as employed by sighted subjects. This

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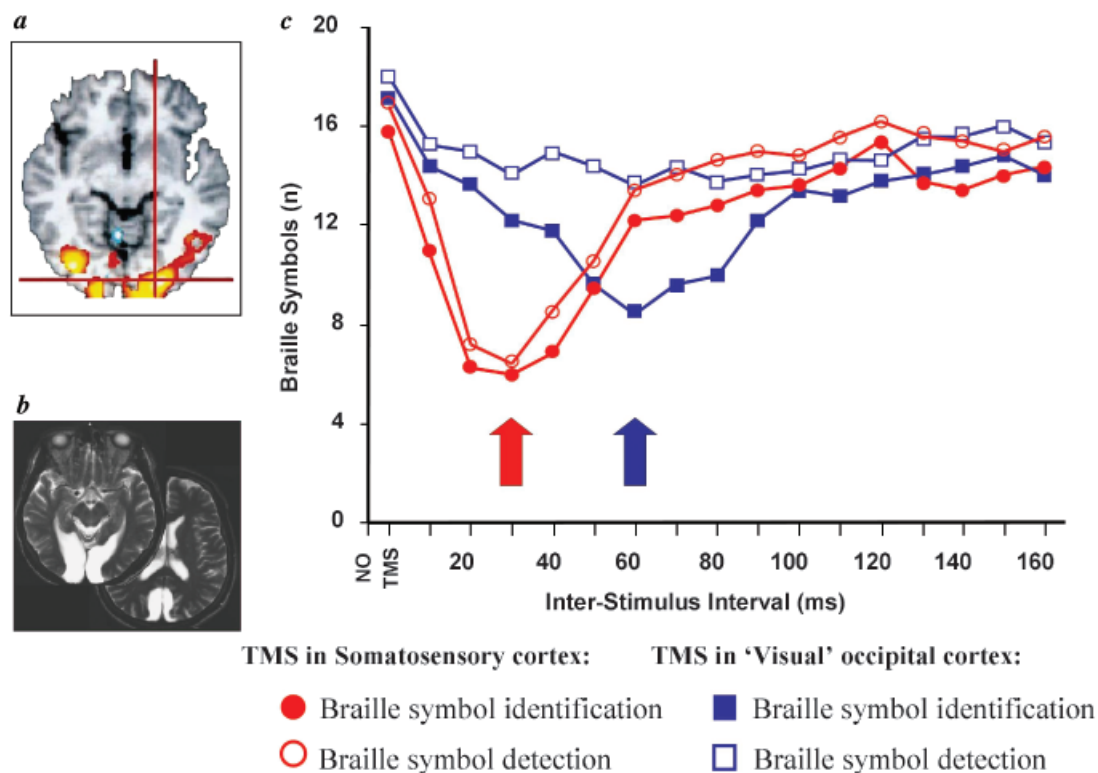
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dependence on language and memory may also be accompanied by the development of superior capabilities for these functions (Amedi, Raz, Pianka, Malach, & Zohary, 2003). This raises the question: Does the part of the brain used by a sighted person to recognize objects or read visually (in other words, to see) play a role in a blind person reading through touch and relying heavily on verbal language? Growing experimental evidence suggests that it does.

### THE OCCIPITAL CORTEX IN THE BLIND: TOUCHING THE DOTS

The development of functional neuroimaging techniques (such as functional magnetic resonance imagery, fMRI, and positron emission tomography, PET) allows researchers to observe with unprecedented detail brain activity as a function of behavior. Several groups have used these techniques to study activation in the occipital cortex during nonvisual sensory tasks. Sadato et al. (1996) demonstrated activation on both sides of the “visual”

cortex, including the primary visual cortex, while early-blind subjects (usually defined as those blinded from birth up to the age when learning to read Braille begins, between 4 and 6 years) performed a Braille-reading task (Fig. 1a). Activation of the primary visual cortex was also evident (though to a lesser extent) in non-Braille tactile-discrimination tasks such as angle discriminations (judging the angles of tactile lines created from Braille dots), but the passive sweeping of the fingers over a homogeneous pattern of Braille dots did not lead to such activation. Subsequent investigators have further refined and extended these early findings, addressing the role of imagery, the differences between people who are early blind and those who are late blind (i.e., subjects blinded after the age of 6 years, usually after acquiring reading abilities), and the role of tactile versus verbal or linguistic aspects of the task (for reviews see Burton, 2003; Pascual-Leone, Amedi, Fregni, & Merabet, 2005; Roder, & Neville, 2003). Cross-modal plasticity (i.e., brain changes in the processing and representation of different senses) in the occipital cortex of the blind has also been reported in the auditory



**Fig. 1.** Brain image (a) showing activation in the occipital lobe during Braille reading in an early-blind subject (modified from Sadato et al., 1996); brain scan (b) of a congenitally blind woman who was rendered unable to read Braille following a bilateral occipital stroke (area shaded in gray indicates area of highly damaged tissue within the occipital cortex on both sides; modified from Hamilton et al., 2000); and effects of temporary disruption of the somatosensory cortex or of the “visual” occipital cortex using single-pulse transcranial magnetic stimulation (TMS) on tactile recognition of Braille characters in congenitally blind subjects (c). The TMS pulse was delivered at different times (interstimulus interval) after presenting a tactile stimulus to the pad of the index finger. The graph displays the number of tactile stimuli detected (open circles/squares) and correctly identified (filled circles/squares). Disruption of the somatosensory cortex led to a decrease in the number of detected and identified letters at an interstimulus interval of 30 ms (red arrow). Disruption of the occipital cortex led to a decrease in the number of identified letters only at an interstimulus interval of approximately 60 ms (blue arrow; modified from Hamilton, Keenan, Catala, & Pascual-Leone, 2000).

domain, suggesting that such plasticity in cases of early sensory loss might be a general principle (e.g. Gougoux, Zatorre, Lassonde, Voss, & Lepore, 2005; Roder, & Neville, 2003).

It is important to realize that patterns of activation revealed by functional neuroimaging establish an association between activity in a given region or network and the performance of tasks, rather than proving a causal link (e.g., activation of the occipital cortex might be due to irregularities in blood flow in the blind rather than to the area's contributing to Braille reading). To establish a causal link, neuroscientists have classically relied on studying patients with localized brain damage. Indeed, a serendipitous clinical case of an early-blind woman, once highly proficient at reading Braille but later rendered unable to do so following a bilateral occipital stroke, supports the notion of a causal link between the ability to read Braille and occipital function (Hamilton, Keenan, Catala, & Pascual-Leone, 2000; Fig. 1b).

In an experimental setting, transcranial magnetic stimulation (TMS) can be used as a means to recreate the behavioral deficits observed following damage to specific areas of the cortex. Briefly, a TMS device generates a rapidly alternating electromagnetic pulse that travels through the scalp and can temporarily disrupt cortical activity. Thus, in essence, TMS represents a method of creating a "virtual lesion" in a focal, reversible, and noninvasive manner (Pascual-Leone, Walsh, & Rothwell, 2000). Cohen and colleagues used TMS to study early-blind subjects performing a Braille-identification task (for review, see Pascual-Leone et al., 2005). When TMS was delivered to the occipital cortex, tactile identification of Braille letters was impaired. In contrast, TMS of the occipital cortex in sighted controls did not impair their ability to identify embossed Roman letters by touch. Interestingly, during occipital TMS, blind subjects also reported distorted tactile perceptions and, occasionally, feeling additional ("phantom") Braille dots.

The functional significance of the occipital activation during Braille reading was further evaluated using single-pulse TMS, allowing assessment of the timing of information processing (Pascual-Leone, Walsh, & Rothwell, 2000). A disruptive TMS pulse was applied at varying time intervals following the presentation of a Braille symbol to the subject's index finger (Hamilton, & Pascual-Leone, 1998). In sighted and blind subjects, TMS delivered to the somatosensory cortex (the part of the brain, located in the anterior parietal cortex, involved in the perception of touch) interfered with the detection of a tactile stimulus presented 20 to 40 milliseconds earlier to the pad of the index finger (Fig. 1c; only the early-blind group data is shown), while occipital stimulation had no effect on detection. However, TMS to the occipital cortex disrupted processing of Braille symbols only in congenitally blind subjects and when intervals between pulses were 50 to 80 milliseconds (Fig. 1c). Contrary to the findings after sensorimotor TMS, following occipital TMS blind subjects generally knew whether a peripheral stimulus had been presented. However, they were unable to tell what Braille symbol

it was. These results suggest that in early-blind subjects, tactile information reaches the cortex by the somatosensory cortex, which is engaged in detection, while the occipital cortex contributes later to the perception of tactile stimuli.

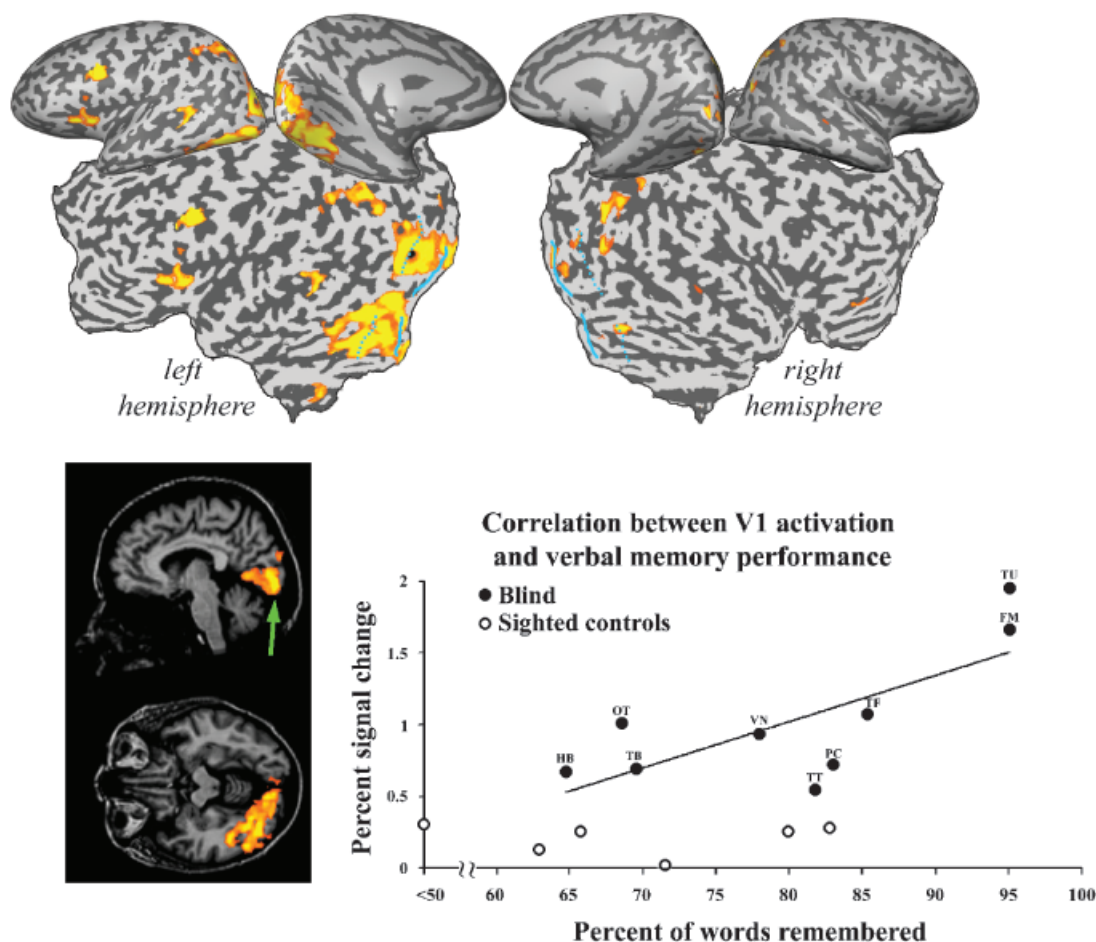
### INSIGHTS FROM STUDIES IN BLINDFOLDED SUBJECTS

Complete but temporary visual deprivation in sighted subjects (i.e., 5 days of blindfolding) seems to be sufficient to lead to recruitment of the primary visual cortex for tactile and auditory processing (i.e. activation of visual areas by Braille-letter identification, touch, and hearing; see Pascual-Leone, Amedi, Fregni, & Merabet, 2005 for review). The speed of these functional changes in sighted individuals is such that it is highly improbable that new cortical connections are established. Therefore, somatosensory and auditory connections to the occipital cortex must already be present and are presumably "unmasked" under these experimental conditions. Nevertheless, these findings in the tactile domain, comparable to previous findings in the blind, do not show that the mechanisms in blindfolded subjects are identical to those in blindness (i.e., a similar result of higher primary visual cortex processing in the two groups could be mediated by release from inhibition during blindfolding or via establishing new connections in blind subjects). Thus, more studies are needed to address this important issue.

### BEYOND TACTILE PROCESSING: OCCIPITAL ACTIVATION IN HIGH-LEVEL COGNITIVE TASKS

Recent neuroimaging studies in the blind have demonstrated occipital cortex activation during tasks requiring auditory-verb generation, during semantic-judgment tasks, and during speech processing (See Burton, 2003; Pascual-Leone, Amedi, Fregni, & Merabet, 2005; Roder, Stock, Bien, Neville, & Rosler, 2002). In one study, Burton and colleagues reported differences in brain activity between early-blind and late-blind subjects. The researchers used a verb-generation task, in which subjects were instructed to generate a verb in response to a noun cue (e.g., for "cake" the subject would have to generate "bake") presented in Braille or via hearing. Activation in the occipital cortex was evident in both groups (showing some left-hemisphere dominance, especially in the auditory version), but it was more prominent in subjects who were early blind (Burton, 2003). The sighted control group showed activation in typical language-related areas (e.g., Broca's area, in the prefrontal cortex) but no occipital activation.

Amedi and colleagues found similar results for auditory-verb generation in congenitally blind subjects. They also reported strong activation of the occipital cortex on the left side—including along the calcarine sulcus (an area corresponding to the primary visual cortex in sighted people)—to a verbal-memory



**Fig. 2.** Brain activation in congenitally blind subjects during a verbal-memory task (involving no sensory stimulation) and correlation between activation and verbal-memory performance for both blind subjects and sighted controls. Yellow/orange areas in upper and lower-left panels show activation. Verbal-memory activation can be seen across the entire cortex of blind subjects; and only in blind subjects was activation also found in visual areas, mainly in the left hemisphere (compare the activation patterns in the left and right brain reconstructions; areas corresponding to the primary visual cortex and adjacent visual areas in sighted people are denoted by continuous and dashed cyan lines respectively). Subjects were tested on the percent of words they remembered 6 months after the scan; in general, blind subjects remembered more words and showed greater activation of the primary visual cortex (V1; activation is measured as percent signal change) than the sighted controls did. Only blind subjects also showed significant correlation between brain activity and performance in this task and general verbal-memory abilities. Modified from Amedi et al. (2003).

task requiring the retrieval of abstract words from long-term memory (Amedi, Raz, Pianka, Malach, & Zohary, 2003), suggesting that the primary visual cortex can be activated without introducing any sensory input. Notably, blind subjects showed superior verbal-memory capabilities when compared to age-matched sighted controls and to reported standardized population averages. Furthermore, in the blind group alone, a strong positive correlation was found between the magnitude of primary visual cortex activation and individual subjects' verbal-memory capabilities (Fig. 2).

The functional relevance of these findings was demonstrated by showing that TMS of the left primary visual cortex or left occipito-temporal cortex led to a disruption in performance (increase in the error rate) in a verb-generation task (Amedi, Floel, Knecht, Zohary, & Cohen, 2004). The most common error

produced by the TMS was semantic (e.g., “apple” would lead to the verb “jump”), while phonological errors and interference with motor execution or articulation (stuttering and slurring of responses) were rare. These results suggest that language and memory processing in blind people incorporate a widespread network that encompasses “visual” brain areas.

#### PROPOSED CONCEPTUAL FRAMEWORK AND POSSIBLE IMPLICATIONS

It seems reasonable to presume that in the context of visual deprivation, the brain reorganizes to exploit the sensory inputs at its disposal. In this context, the functional and structural identity of the occipital cortex may switch from processing visual information to the processing of information from other senses.

Alternatively, it is possible that the occipital cortex inherently possesses the computational machinery necessary for the processing of nonvisual information. According to this hypothesis, the occipital cortex might be viewed as an “operator” of a given function based on the best-suited input available. When sight is present, visual input may be deemed as ideal for the operation of the occipital cortex, to the point of suppressing or masking inputs from other senses. In the absence of visual input, the occipital cortex may employ nonvisual inputs for its operation (Pascual-Leone & Hamilton, 2001).

Thus, two possible mechanisms may account for the reviewed changes in occipital function. The first represents *de novo* cross-modal plasticity, in which new sensory associations and connectivity patterns are created in response to visual deprivation (Burton, 2003). A second mechanism represents expression of normal physiology, in which functions that are normally inhibited or masked in the sighted are revealed by visual loss. We suggest here that these two mechanisms are inextricably linked. The unmasking of pre-existing connections and shifts in connectivity are rapid, early-occurring plastic changes, which can lead, if sustained and reinforced, to slower-developing, but more permanent, structural changes, such as the establishment of new neural connections. This can account for the rapid recruitment of occipital cortex function observed in blindfolded subjects and the difference in the magnitude of the reorganization between early- and late-blind subjects. This hypothesis also results in the prediction that careful task choice and experimental design will reveal nonvisual roles of the occipital cortex in sighted subjects. Indeed, such nonvisual roles can be demonstrated for object recognition (Amedi et al., 2001), processing of orientation (Zangaladze et al., 1999), and judging of distance between Braille dots (Merabet et al., 2004; for review, see Amedi, Von Kriegstein, Van Atteveldt, Beauchamp, & Naumer, 2005). Therefore, the occipital cortex is not “simply” visual, but rather participates in tactile, auditory, and perhaps even linguistic tasks.

This set of results might also have important implications regarding teaching, learning, and rehabilitation strategies in persons with developmental disabilities and in stroke and accident victims. The results from late-blind and blindfold studies support the notion that the adult brain is capable of undergoing considerable plastic change throughout the lifespan (Kaas, 1991; Pascual-Leone, Amedi, Fregni, & Merabet, 2005). Fundamental principles underlying neural plasticity in response to visual deprivation may be applicable across neural systems (Pascual-Leone, Amedi, Fregni, & Merabet, 2005; Bavelier & Neville, 2002). However, it is important to remember that plasticity is an intrinsic property of the human nervous system and plastic changes may not necessarily lead to a behavioral gain. Plasticity is the mechanism that underlies development and learning, but it is also a potential cause of pathology. Our challenge is to modulate neural plasticity for each individual’s optimal behavioral gain. This might be possible, for example,

through behavioral modification or brain-stimulation techniques. In this respect, the results from the week-long blindfold study suggest that release from inhibition might facilitate increased participation of the visual cortex in auditory and tactile tasks and enhance functional gain. The mechanisms and conditions that promote recruitment of the visual cortex for high-level cognitive functions and the resulting superior verbal-memory capabilities in the early blind remain unclear. Strategies to promote such plastic changes are important to aid blind individuals to compensate for their disabilities.

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### Recommended Reading

- Amedi, A., Raz, N., Pianka, P., Malach, R., & Zohary, E. (2003). (See References)
- Burton, H. (2003). (See References)
- Hamilton, R.H., Pascual-Leone, A. (1998). (See References)
- Merabet, L., Rizzo, J.F., Amedi, A., Somers, D., & Pascual-Leone, A. (2005). What blindness can tell us about seeing again: Merging neuroplasticity and neuroprostheses. *Nature Reviews Neuroscience*, 6, 71–77.
- Pascual-Leone, A., & Hamilton, R. (2001). (See References)
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### REFERENCES

- Amedi, A., Floel, A., Knecht, S., Zohary, E., & Cohen, L.G. (2004). Transcranial magnetic stimulation of the occipital pole interferes with verbal processing in blind subjects. *Nature Neuroscience*, 7, 1266–1270.
- Amedi, A., Raz, N., Pianka, P., Malach, R., & Zohary, E. (2003). Early ‘visual’ cortex activation correlates with superior verbal-memory performance in the blind. *Nature Neuroscience*, 6, 758–766.
- Amedi, A., Von Kriegstein, K., Van Atteveldt, N., Beauchamp, M.S., & Naumer, M.J. (2005). Functional imaging of human crossmodal identification and object recognition. *Experimental Brain Research*, 166, 559–571.
- Bavelier, D., & Neville, H. (2002). Cross-modal plasticity: Where and how? *Nature Reviews Neuroscience*, 3, 443–452.
- Burton, H. (2003). Visual cortex activity in early and late blind people. *Journal of Neuroscience*, 23, 4005–4011.
- Gougoux, F., Zatorre, R.J., Lassonde, M., Voss, P., & Lepore, F. (2005). A functional neuroimaging study of sound localization: Visual cortex activity predicts performance in early-blind individuals. *PLoS Biology*, 3, 324–333.
- Hamilton, R.H., Keenan, J.P., Catala, M.D., & Pascual-Leone, A. (2000). Alexia for Braille following bilateral occipital stroke in an early blind woman. *Neuroreport*, 7, 237–240.
- Hamilton, R.H., & Pascual-Leone, A. (1998). Cortical plasticity associated with Braille learning. *Trends in Cognitive Science*, 2, 168–174.

- Kaas, J.H. (1991). Plasticity of sensory and motor maps in adult mammals. *Annual Reviews of Neuroscience*, *14*, 137–167.
- Pascual-Leone, A., Amedi, A., Fregni, F., & Merabet, L.B. (2005). The plastic human brain cortex. *Annual Reviews of Neuroscience*, *28*, 377–401.
- Pascual-Leone, A., & Hamilton, R. (2001). The metamodal organization of the brain. In C. Casanova & M. Ptito (Eds.), *Vision: From neurons to cognition*, Progress in Brain Research, Vol. 134 (pp. 427–445). Amsterdam: Elsevier.
- Pascual-Leone, A., Walsh, V., & Rothwell, J. (2000). Transcranial magnetic stimulation in cognitive neuroscience—virtual lesion, chronometry, and functional connectivity. *Current Opinion in Neurobiology*, *10*, 232–237.
- Rauschecker, J.P. (1995). Compensatory plasticity and sensory substitution in the cerebral cortex. *Trends in Neuroscience*, *18*, 36–43.
- Roder, B., & Neville, H. (2003). Developmental functional plasticity. In S. Grafman & I.H. Robertson (Eds.), *Handbook of neuropsychology* (2nd ed. Vol. 9, pp. 231–270). Amsterdam: Elsevier.
- Roder, B., Stock, O., Bien, S., Neville, H., & Rosler, F. (2002). Speech processing activates visual cortex in congenitally blind humans. *European Journal of Neuroscience*, *16*, 930–936.
- Sadato, N., Pascual-Leone, A., Grafman, J., Ibanez, V., Deiber, M.P., Dold, G., & Hallett, M. (1996). Activation of the primary visual cortex by Braille reading in blind subjects. *Nature*, *11*, 526–528.