On the Neuroplasticity of the Occipital Cortex in both the Congenitally and Early Blind and Possible Implications for Rehabilitation

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January 4, 2010

Abstract

This paper examines the role of the occipital cortex in the blind, specifically in the early and congenitally blind. Possible non-visual functions of blind occipital cortex are discussed based on findings from MRI, fMRI, PET, microelectrode, TMS, and lesion studies. Representations of tactile, auditory, and memory within the occipital lobe are addressed as hypothetical neuroplastic functions as a result of visual deprivation. Lastly, limitations are noted and suggestions are made for further research, including the possibility of creating rehabilitation devices that could utilize the plasticity of blind visual cortex.

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In North America, over 10 million people suffer from vision loss (American Foundation for the Blind, 2009). Of that 10 million, over 3.5 million live in the United States. These statistics include those who are "visually impaired," or those who possess a visual acuity of 20/40 or less with the best possible vision correction available. To be classified as "legally blind," which will be the focus hereafter, entails a slightly stricter criteria of 20/200 vision with corrective lenses; such a classification can be applied to over one million Americans (Prevent Blindness America, 2008). Specifically, this review will direct attention to studies concerning the early and congenitally blind, as opposed to those who became blind later in life. Those who are congenitally blind have been labeled as "legally blind" since birth and most likely were born blind due to genetic factors or medical complications. Early blindness denotes those who have become blind at some point prior to the age of two (Wan, Wood, Reutens, & Wilson, 2009).

In line with logical deductions, it was once a common belief that the blind had no use for their occipital cortex, an area of the brain that primarily processes visual input. It was also a widespread thought that the occipital cortex simply shrank or deteriorated in the blind. Contrary to these popular notions, it has been shown through magnetic imaging studies that the occipital cortex is neither nonexistent nor useless in the blind. Wanet-Defalque et al. (1988) studied the macroanatomy of occipital cortex in early blind subjects through MRI and found its structure to be "normal" in comparison to controls. In fact, *higher* glucose metabolism in comparison to controls has been found to be present in the visual cortex of the blind and is seen in the form of increased cerebral blood flow. This indicates an even greater usage of the visual cortex in the blind versus sighted individuals (Phelps et al., 1981). A more recent study expounded upon these results by exploring the possible morphological changes in the visual system in those who are congenitally blind. MRI was used to view morphological changes in the optic nerve and tract, along with the occipital cortex, in 12 congenitally blind patients. Structural changes were found, including the thinning of the optic nerve. In fact, the optic nerve, chiasm, and tract were all smaller in blind patients compared to control subjects. However, upon studying the visual cortex, the occipital lobe was found to be morphologically normal in all cases, showing no sign of atrophy or gliotic degeneration (Breitenseher, 1998)

These studies suggest that not only is the occipital cortex still present in the blind, but it is also quite active, as evidenced by the above-normal glucose metabolism that is present. Such increased activity in the visual area of the brain in the blind lends itself to the idea of neural plasticity. Not surprisingly, the hypothesis that the occipital cortex may be used for other non-visual functions has recently become a popular area of research. Here, we examine the possible functionality of the occipital cortex in the congenital and early blind, which includes potential tactile, memory, and auditory uses, along with ways in which such newly acquired functions may serve rehabilitative purposes.

Animal Studies on Blind Occipital Cortex

Interest in the area of plastic functions of blind occipital cortex was first generated with the advent of animal studies on the subject. In a study conducted by Hyvarinen et al. (1981), monkeys' eyelids were sewn shut immediately after birth. The sutures were not removed until a year later, at which time microelectrode recordings were taken in area 19 of occipital cortex. In control sighted moneys, 100% of the neuronal groups studied in area 19 responded only to visual stimuli. This contrasted with the results found in the monkeys that had suffered visual deprivation; only 40% of the neuronal groups in the blind monkeys responded exclusively to visual stimuli. In fact, 20% of the neurons in the lid-sutured group responded solely to somatic movement, including touching another object. From the study, the experimenters were able to conclude that visual deprivation influences the type and number of synaptic pathways that lead to the visual cortex, possibly influencing the access of the occipital cortex to information other than visual input.

Berman (1991) conducted another animal study that showed how the functional organization of the brain might change in the visually deprived. He studied the major pathways leading to the visual cortex in enucleated kittens. The act of enucleating the kittens was carried out between zero and 60 days following birth. It was found that until the fifth week of life, temporary extrinsic connections existed in control kitten brains that projected from auditory and somatosensory areas to the occipital cortex. In the visually deprived kittens, such connections existed until the age of seven months or even beyond. For instance, the pathway from the intralaminar to the visual cortex was twice the normal volume in the enucleated kittens. Essentially, it was found that an early removal of visual stimuli increased the thalamo-cortical connections to the striate cortex. Even some of the cortico-cortico connections were altered, such as the connections present between occipital areas 17 and 18. Overall, the earlier the kittens were enucleated following birth, the more drastic were the connective changes. If such supplementary connections between the visual cortex and somatosensory areas did exist in the enucleated kittens, this would make the idea of crossmodal reorganization of occipital cortex in the blind both easier and more plausible. It is findings such as these in animal studies that provided the inspiration for human studies on the plastic functionality of occipital cortex in the blind.

Human Studies (PET, TMS, fMRI, Lesion) Showing New Occipital Functions in the Blind

Tactile Function

The hypothesis that blind occipital cortex may be used for tactile purposes has been supported by numerous studies. In one study, event related potentials (ERPs) were recorded in the early blind during a tactile reading and non-reading tactile control task. Higher negative potential shifts located in the occipital cortex were recorded in the blind versus sighted persons. Occipital negativity in the blind was greater for both active (Braille reading) and passive touch (raised dots present in a random pattern) compared to the control non-tactile task. Even when arousal level was controlled for, this additional activation in the occipital cortex was still present (Uhl, Franzen, Lindinger, Lang, & Deecke, 1991). This shows that not only is the occipital cortex in the blind active, but it seems to have potential to hold substantial function.

Because of the aforementioned study, it was shown that the blind visual cortex was active for tactile sensations in general, but exactly what type of tactile sensations remained yet unsolved. Sadato et al. (1996) attempted to approach this question through the use of positron emission tomography (PET) to measure occipital activations during Braille reading tactile-discrimination tasks. During these Braille tactile tasks, blind subjects showed activation in both primary and secondary occipital cortex, which contrasted to the deactivation, or decreased cerebral blood flow, seen in sighted controls. Specifically, area 17 of the occipital cortex was most activated in the blind, but activations extended from primary visual cortex to extrastriate areas. A simple touch control task that did not require discrimination was also conducted and elicited no activation in the occipital cortex in either the blind or sighted subjects. This study showed that the occipital cortex in the blind was specifically active for the tactile sensations elicited during Braille reading and other discrimination tactile tasks, not just touch in general.

In order to confirm these findings regarding the plasticity of the occipital cortex in the blind and its activation by Braille reading, lesion studies needed to be conducted to see if the loss of the occipital cortex *inhibited* Braille reading. When this first was attempted, no pre-existing lesions in blind patients were specific enough to test this hypothesis, forcing experimenters to rely on virtual lesion techniques through transcranial magnetic stimulation (TMS). Cohen et al. (1997) conducted such a study, using TMS used to disrupt occipital cortex. The blind subjects used were considered to be early blind. They were instructed to read either Braille or Roman letters that had been embossed. The disruption of visual cortex interfered with reading of Braille and the reading of Roman letters in the blind, both tasks that required skills involving tactile discrimination. TMS over blind striate cortex introduced tactile perception errors, creating the sensation of phantom dots, missing dots, and faded dots. On the contrary, TMS over the occipital lobe in sighted control subjects neither interfered with their ability to recognize or feel raised dots of the embossed Roman letters, nor created abnormal sensations such as the “phantom dots” experienced by the blind. Once again, the neural plasticity of the occipital cortex in the early blind was confirmed, as was the possibility of tactile functionality in regards to Braille reading.

Eventually, experimenters were able to find blind patients with specific enough occipital damage to carry out actual lesion studies. Hamilton et al. (2000) conducted a case study, examining a 63-year-old woman who had been blind since birth. She had since obtained a bachelor’s degree and worked at a Spanish radio station where she extensively used Braille, about four to six hours a day, and was able to read at an incredible speed. One day after feelings of lightheadedness, she suddenly collapsed at work and was said to have suffered an ischemic stroke that lesioned her occipital lobes bilaterally. Following the stroke, she reported that Braille dots “felt flat” and that it seemed as if she were wearing “thick gloves.” She could not determine the meaning of the letters. Her tactile impairments were limited only to Braille; she was able to identify the surfaces of all objects and surfaces by touch. An MRI revealed only extensive bilateral occipital lobe damage and noted that the language brain regions were not damaged. This supports the previous TMS studies and gives evidence for the involvement of the striate and extrastriate cortex in Braille reading.

All of the studies mentioned thus far concerning tactile function in occipital cortex have implicated the striate cortex, also known as primary visual cortex (V1). However, not all of the findings are consistent with primary occipital cortex activation. Buchel et al (1998) did a PET study of six congenitally blind subjects and three late blind subjects who lost their sight after puberty. The subjects were scanned while reading real and non-real (random dot pattern) Braille words. Congenitally blind subjects showed extrastriate occipital cortex activations during the Braille reading of real words. Late-blind subjects showed this extrastriate activation while reading real Braille words in addition to activation in primary visual cortex. These results suggest that the extent of reorganization depends on timing of onset of blindness, particularly if blindness occurred before or after puberty, as puberty is an important milestone for visual cortex development in humans. Why is there more plasticity in the congenitally blind? Emergence of crude clusters in V1 is not affected by blindness, but refinement of these clusters is affected: early visual deprivation alters receptive field properties in area 17 and prevents formation of specific projections from the thalamus, thus allowing for the existence of more cross-modal projections to exist. By the time puberty occurs, projections between striate and extrastriate cortex have developed normally in those who have not suffered visual deprivation. Also, the difference between late and congenitally blind is that late blind have been exposed to visual stimuli at some point. Late blind subjects reported that they transform tactile stimuli into a visual image (they “see” Braille dots in their mind’s eye). Perhaps this V1 activation is therefore due to mental imagery. However the following caveat presents itself: why then does mental imagery in other studies fail to activate V1 in normal subjects? One hypothetical answer to that question is that the late-blind persons have an absence of competing thalamic inputs.

Cortico-cortical reorganization is thought to be responsible for the activation of extrastriate visual areas by tactile stimuli (Rauschecker, 1992). Area 7 of the extrastriate cortex in particular is thought to be a contributing factor, as the number of neurons responding to tactile stimuli in area 7 has been shown to be greater than control subjects in microelectrode recording studies (Carlson, 1987). As a whole, these studies offer strong evidence that the blind occipital cortex takes on the function of tactile discrimination. Whether this tactile function activates both the primary and extrastriate occipital cortex, or only the extrastriate areas, remains to be uncovered.

Verbal Memory Function

Studies have elucidated the possible function of blind occipital cortex in verbal memory. In the blind, the absence of visual cues may increase the dependence on memory, especially verbal memory. The occipital cortex in the blind is thought to be involved in tactile tasks, as previously mentioned, along with verbal memory, and various auditory tasks. All of these different functions show that the visual cortex in the blind may form new specialized characteristics as part of a “division of labor.” Amedi et al (2003) used fMRI to examine congenitally blind persons during a verbal-memory and Braille reading task to see if such a division of labor existed. Evidence was found for a reorganized and specialized occipital cortex on the anterior-posterior axis. Anterior regions, including the lateral occipital cortex, showed preference for Braille, and posterior regions, including V1, showed preference for verbal memory; this occipital activation was not found in sighted controls.

Visual processing in the sighted brain is organized in a hierarchical manner. This hierarchy is reversed in the blind: early retinotopic regions process abstract concepts such as verbal memory and concrete sensory representations, like tactile Braille reading, are present in the more anterior regions (Amedi et al., 2003). The topographic division within the occipital cortex may explain the previously described discrepancy as to the exact location of the “tactile” functional center; perhaps its location is not limited to an exact location such as primary occipital cortex or extrastriate cortex, but moreover the general area of anterior visual cortex.

Overall, the blind were superior in verbal-memory tasks and the amount of V1 activation correlated with the extent of their ability to remember in the verbal-memory task. Training does improve performance in verbal memory. However, even when trained, occipital cortex regions were not activated in sighted individuals. Visual deprivation is most likely necessary to develop activations in the occipital cortex in response to verbal memory. Reciprocal connections between the medial temporal lobe and V1 are found in the normal developing brain. For those who are congenitally blind, these feedback pathways may be even more numerous since competition from visual input is not an issue (Amedi et al., 2003). The increased number of feedback pathways in the blind thus allows for greater neural plasticity.

Enhanced Speech Processing Function

There is a close connection between the biological inputs and development of a functional neural system, such as the altered organization of language functions in the deaf. A study by Roder et al. (2002) wanted to see if the of grouping of brain structures responsible for language is also altered in the blind. This study used natural auditory language stimuli and fMRI to examine activations during speech comprehension. Ten congenitally blind subjects were used, all professional readers of Braille and were instructed to listen to semantic and non-semantic sentences varying in difficulty. Typical language perisylvian areas in the left hemisphere were activated as a result. The results also showed that speech comprehension activated areas in the blind not activated in the sighted group, such as the extrastriate and primary visual cortex. Overall, semantic sentences elicited higher cerebral blood flow in *both* hemispheres.

These results suggest that increased specialization of brain tissue may not develop to the same extent in blind individuals. Since there is less competition for synaptic space, the blind occipital lobe may be able to participate in non-visual functions such as language processing. Some caveats do exist however: in the previously mentioned lesion study by Hamilton et al. (2000), removal of the occipital lobe due to a stroke caused Braille alexia but preserved speech comprehension. Therefore, activation of the occipital lobe may provide support in language comprehension and act as a compensatory mechanism in the blind, but may not be sufficient on its own. Young blind children, for example, show delays in language processing, but this delay disappears as they get older. These children actually become more advanced and eventually have faster speech processing than normal sighted individuals as the occipital region is recruited and helps to act as a compensatory system (Roder et al., 2002).

Sound Location Function

The occipital lobe in the early blind is also thought to be used for sound location. Kujala et al. (1992) completed a study that utilized ERPs to change the location of a repetitive sound in the early blind. The goal of the study was to determine if occipital lobe in the blind participates in auditory spatial information through the use of ERPs by comparing sound location in blind versus sighted individuals. The auditory stimuli were given with the instructions of either “attend” or “ignore.” When a deviant stimulus was present, a mismatch negativity (MMN) signal occurred, even when the stimulus was unattended. When the stimulus was attended, the N2b component signal was elicited. This N2b component in the blind was located further towards the caudal area of the brain, in the occipital cortex, compared to the location of the N2b component in the sighted. In a parallel study conducted by Alho et al (1993), ERPs were recorded in blind subjects while they listened to auditory stimuli. Once again, the negative potential signal elicited by attended stimuli was located in a part of the brain posterior to that in sighted controls, mainly in the occipital lobe. These two studies together suggests that visual cortex in the blind also participates in attention to auditory sound location, thus reaffirming the notion of plastic changes in the brain following the loss of vision

Possible blind rehabilitation using the evidence of occipital cortex plasticity

De Volder (1999) did a study that investigated the plasticity of the occipital cortex in interpreting new sensations, such as sensory substitution prosthesis, while using an echolocation device. This PET study examined the brain areas that are activated while operating the device in five male early blind subjects. The echolocation system was used for two tasks involving spatial distance and direction. The subjects were told to locate obstacles while using the echolocation device (composed of spectacles, three ultrasonic transducers and two earphones). Subjects were provided with training sessions, during which they learned to locate walls, doors, and stairs. In the control condition, subjects simply had to orient their head towards the location of the sound stimuli. In the experimental condition, subjects wore the sound location device and had to determine both a pole's location and distance while PET was utilized.

As has already been mentioned, there is an elevated glucose metabolism in blind occipital cortex. The metabolism level increases even further with the use of the echolocation device. The highest metabolic rates were found in both the primary and extrastriate visual cortex areas in the early blind. This elevation in occipital cortex activity was not seen in sighted controls. These results suggest a prolonged plasticity in visually deprived occipital cortex that could be harnessed for rehabilitative purposes. While operating the echolocation device, auditory signals are being used to determine distance information, which is usually processed visually. No neural brain tissue has developed in the human brain for the purpose of determining absolute distance information via audition, which makes this a new kind of information that was being processed by the visual cortex. If we can "induce" the occipital lobe to carry out new functions such as these, blindness rehabilitation may be possible through the use of advanced substitution prosthesis devices.

Limitations

Limitations exist in the studies mentioned in this review. In the study conducted by Breitensher (1995) which concluded that the occipital cortex in the blind is normal, it should be noted that area V1 is a highly complicated structure, and it is hard to see everything with MRI. 3-D techniques would assist with resolution and could show that the occipital cortex may not actually be “normal.” Even the verbal memory study by Amedi et al. (2003) noted that the activation in blind occipital cortex in response to recalling verbal cues could be the result of confounding factors such as differences in arousal or attention. In the lesion study that resulted in Braille alexia, it is not possible to know if the subject could not comprehend the Braille symbols or if she was unable to detect the Braille from a tactile end. However, it is thought her language abilities and abilities to detect other tactile stimuli were intact, so most likely it was actually a Braille alexia specifically (Hamilton et al., 2000). In the echolocation device study by De Volder (1999), the FDG tracer that was used was suboptimal and did not always allow for repeat scans. Additionally, in that study, as well as other mentioned studies, men were usually the only types of subjects used for various reasons, including availability and ethical reasons in relation to invasiveness of the studies. The question remains: do these results apply to women also?

A general limitation is that the degree of neural plasticity and cross-modal functionality of blind occipital cortex seems to greatly differ according to the age at which blindness first occurred. This is supported by findings from the study by Buchel et al. (1998) which noted that differences in tactile activations within the visual cortex were recorded for the congenitally blind compared to late blind individuals. Other studies support the finding that differences exist within the occipital cortex of early versus late blind, such as a study concerning auditory perception that was conducted by Wan et al. (2009). The study consisted of 33 blind (11 congenital, 11 early blind, 11 late blind) participants and 33 sighted control subjects who completed auditory tasks. Performance on these auditory tasks was remarkably better in both the congenitally and early blind participants, but not for the late blind or sighted controls. The advantage was even more noticeable for those who had been blind since birth.

It is apparent based on these studies that the extent of functional plasticity within the occipital cortex may be age dependent. Thus, the functions of blind occipital cortex mentioned in this review, such as tactile, verbal memory, sound location, and speech comprehension, may be limited to the congenital and early blind. This also has important implications for rehabilitative sensory substitution devices, which may only be applicable to the early blind group as well.

Conclusion

Despite the noted limitations, plasticity of the occipital cortex in the form of acquiring non-visual functions in blind patients seems quite probable. Higher measures of cerebral blood flow, negative event-related potentials, and higher ratio of oxygenated to deoxygenated flow in fMRI studies all showed increased levels of activity within the blind occipital cortex compared to sighted controls. Both virtual and actual lesion studies confirmed the functionality of visual cortex, as such new plastic functions were lost when lesions occurred. Considerable evidence was mentioned in support of the hypothesis that the blind visual cortex has functional roles in touch (specifically Braille), verbal memory, speech comprehension, and sound location. Increased subcortico-cortical and cortico-cortical connections in the brains of the blind may contribute to this plasticity as well as the lack of competition from visual input. Most of these functions are currently only found in the brains of the congenital and early blind. More research needs to be conducted to see which specific plastic functions, if any, are found in the visual cortex of the late blind. Of considerable importance is the need to apply these cross-modal functions of early blind occipital cortex to rehabilitative devices. Substitutive sensory devices could pave the way to vision restoration to the millions who have lost both their sight and sense of hope.

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