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Neural Reorganization Following Sensory Loss: The Opportunity Of Change

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Abstract

Growing evidence suggests that sensory deprivation is associated with dramatic crossmodal neuroplastic changes in the brain. In the case of visual and auditory deprivation, there is functional recruitment of brain areas normally associated with the sense that is lost by those sensory modalities that are spared. Furthermore, these changes seem to underlie adaptive and compensatory behaviours observed in both blind and deaf individuals. Although there are differences between these two populations due the very nature of the deprived sensory modality, there seem to be common principles regarding how the brain copes with sensory loss and the factors that influence how neuroplastic changes come about. Here, we discuss crossmodal neuroplasticity with regards to behavioural adaptation following sensory deprivation and highlight the possibility of maladaptive consequences within the context of rehabilitation.

A plastic brain in a multisensory world

Equipped with multiple senses and specialized sensory organs, we capture and interact with a rich multisensory world. The unified and salient nature of our sensory experiences is the product of extensive and dynamic neural connections, which in turn are highly influenced by our own experiences and developmental constraints. Current evidence supports the notion that multisensory integration serves to enhance overall perceptual accuracy and saliency through **cooperative advantages** [1, 2] and provides for a redundancy of cues necessary to fully characterize objects in our environment [3]. Interestingly, this same integrative strategy and organization might also account for compensatory behaviours that follow the loss of a sensory modality.

Traditionally, life without a particular sense has been viewed as “impoverished” and many early theories postulated that sensory deprivation would have devastating effects on development, learning and cognitive behavioural performance (e.g. [4, 5]). The “deficiency” theory purports that a lack of perceptual sensory experience leads to an overall impairment in cognitive task performance given that proper multisensory integration can only result from the normal development of each individual sense. However, it is clear that despite facing formidable challenges, blind and deaf individuals make striking adjustments to their sensory loss in order to interact effectively within their environment. Growing evidence from both human and animal research strongly suggest that these adaptations are inextricably linked to changes occurring at multiple levels of the brain [6]. In particular, it seems that these changes not only involve areas of the brain responsible for the processing of remaining senses, but also areas normally associated with the processing of the sensory modality that is lost. Furthermore, these changes may translate into behavioural skills and

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task performance levels that are equal and in certain cases even superior, to that of individuals with intact sensory function. In other situations however, neuroplastic changes may prove to be maladaptive, particularly in light of rehabilitative efforts attempting to restore sensory function after it has been lost or fails to develop. Thus, at one extreme there seems to be an underestimation of the adaptive potential of the brain whereas at the other, there is an assumption that neuroplasticity always leads to positive and advantageous outcomes. What is clear is that understanding the nature of these neuroplastic changes is important not just in terms of establishing the brain's true adaptive potential, but also in elucidating intervening developmental constraints and guiding future rehabilitation strategies. It is also important to highlight that the study of neuroplasticity represents an extremely broad field that is investigated at multiple levels from molecules, to neural systems, to behavior. Much of the seminal work regarding neuroplasticity has arisen from investigating the somatosensory and motor systems. Here, we will focus on behavioral and neurophysiological evidence in relation to visual and auditory deprivation (for work regarding sensorimotor plasticity, the reader is directed to a number of reviews on this subject[7–9].

The adaptation to sensory loss

The case of blindness

There has long been anecdotal evidence that blind individuals somehow compensate for the loss of vision through more effective use of their remaining senses [10, 11]. A systematic review of this issue reveals that blind individuals (particularly, when blind from birth or very early in life) demonstrate comparable and in some cases even superior, behavioural skills compared with sighted subjects. This includes finer tactile discrimination thresholds [12–15] and in the auditory domain, superior performance in auditory pitch discrimination [16] and spatial sound localization [17–20]. Superior performance has also been shown in various other behavioural and cognitive tasks including spatial navigation skills [21], speech discrimination [22] and verbal memory recall [23, 24].

Given that the blind rely heavily on touch and hearing to interact with their environment, it would seem reasonable to suspect that neurophysiological changes would manifest themselves within regions of the brain responsible for somatosensory and auditory processing respectively. Indeed, expansion and reorganization of the cortical finger representation has been reported in blind proficient Braille readers (detected by somatosensory evoked potentials [25] and magnetic encephalography (MEG) [26, 27]). This reorganization has been interpreted to reflect an adaptation that might allow for more enhanced processing and efficient reading skills in these individuals [26, 27]. Changes at the level of auditory cortical areas in the blind have also been investigated. For example, responses to tone bursts and tonotopic mapping studies (using MEG) have revealed an expansion in areas responsive to auditory stimuli and signal response latencies (specifically the **N1 potential**; associated with acuity in central auditory areas) are significantly decreased in blind compared with sighted controls [28]. In a recent functional magnetic resonance imaging (fMRI) study, signal alterations observed within auditory cortex of early blind individuals were consistent with evidence of more efficient processing of auditory stimuli as opposed to an actual altering of inherent patterns of tonotopic organization[29]. Structural changes outside of somatosensory and auditory cortical areas have also been reported. For example, superior spatial navigation performance in the blind has been correlated with a larger volume of the hippocampus (assessed by morphometric MRI [21]), a structure with a well established role in navigation and spatial memory[30].

In parallel to these reported physiological and morphological changes, is the observation that areas within the occipital cortex (normally attributed to visual processing) are functionally

recruited to process non-visual information obtained from intact sensory modalities (figure 1 A). Using various neuroimaging methodologies, this form of crossmodal plasticity has been demonstrated repeatedly [31, 32] and numerous subsequent reports have demonstrated task specific activation related to tactile processing such as Braille reading [33–36], haptic object identification [37] as well as identifying objects using visual-to-tactile based **sensory substitutive devices (SSD)** [38]. A similar account also seems to emerge regarding the recruitment of occipital visual cortical areas in response to auditory related stimuli. A series of neuroimaging studies have demonstrated crossmodal activation of occipital cortical areas for the processing of sounds, including sound source discrimination tasks [39], auditory motion perception [40], auditory change detection [41] and in sound localization [17, 42]. Furthermore, occipital cortex activation has also been reported in conjunction with auditory linguistic tasks such as speech processing [43], semantic judgment tasks [44], auditory verb-generation [45] and verbal-memory tasks [23]. Finally, similar to observations within the tactile domain, the use of visual-to-auditory based SSDs is also associated with activation within occipital cortical areas [46–49].

The specific cortical areas implicated in this form of crossmodal plasticity (e.g. primary versus higher order visual areas) vary across studies and are likely related to the behavioural tasks being performed. It is also important to note that considerable variability exists in terms of the spatial and temporal resolution of the methodologies used, the nature of the task and analyses performed and the types of patients investigated, making comparisons across studies difficult. However, there is direct experimental and clinical evidence supporting the notion that the recruitment of occipital areas is indeed causally related to compensatory behaviours in the blind. The former comes from a series of studies demonstrating impairments in crossmodal related behavioural tasks following the transient and localized disruption of occipital cortex function with transcranial magnetic stimulation (TMS) [50]. For example, TMS delivered to the occipital cortex impairs Braille reading performance in proficient Braille readers [51–53]. Using a similar approach, TMS delivered to occipital cortical targets has been shown to disrupt verb-generation performance [54] and also the use of auditory based SSD systems [48, 55]. Within the clinical setting, there is also the case report of a congenitally blind patient rendered alexic for Braille after suffering a bilateral occipital stroke [56]. Although the patient could discriminate everyday objects by touch, she was no longer able to read Braille and showed striking deficits in tasks requiring fine tactile spatial discriminations [56, 57]. The deficits described in this clinical case are in line with the functional impairments described following reversible cortical disruption using TMS. Taken together, these findings suggest that the recruitment of occipital cortex in high-level cognitive processing and within the context of visual deprivation is indeed functionally relevant.

The case of deafness

As with the blind, the deaf are highly reliant on their intact senses to interact with their surroundings. For example, deaf individuals use visual or tactile stimuli as means to alert attention and many interact through visual-spatial based forms of linguistic communication such as sign language. As a corollary to the findings described in the blind, behavioural evidence supports the notion that deaf individuals show superior skills in certain perceptual tasks compared with hearing control subjects (figure 1 B). For example, enhanced tactile sensitivity (using vibrotactile stimuli) has been reported [58]. In the visual domain, deaf subjects perform better than hearing controls in distinguishing the emotional expression and local facial features [59, 60]. Various studies have also shown that deaf individuals are also better than hearing controls in performing peripheral visual tasks and distributing attention to the visual periphery [61–64]. This augmentation of attentional resources towards the periphery might be adaptive in nature and serve as a compensatory means to direct attention

or orienting towards objects of interest outside the central field of view (see [62]). Superior performance in visual motion detection and discrimination tasks have been described in the deaf particularly with respect to the right visual field [65, 66]. This right visual field advantage might be related to the lateralization of language function, which is typically ascribed to the left hemisphere. Thus, there may be a preferential association regarding the processing of motion information within the right visual field and the left (i.e. contralateral) hemisphere normally associated with language processing [65, 66].

In deaf humans, there seems to be less evidence of dramatic morphological changes within brain areas processing intact sensory modalities. In one study aimed at addressing this question, no differences in responsivity or in the size of early visual cortical areas (assessed with fMRI) were observed in deaf subjects compared with hearing controls [67]. It is important to note however that this lack of observed changes does not rule out the possibility of potential morphological differences in higher order visual areas or even other sensory modalities. Thus, further investigation of this issue seems necessary. Interestingly, and parallel to what has been described in the blind, there is evidence of crossmodal recruitment of auditory cortical areas implicating tactile, language and visual processing tasks. For example, activity within the auditory cortex in response to vibrotactile stimulation (detected by MEG) in congenitally deaf subjects [68] and vibration stimuli derived from speech and fixed frequencies in early deaf subjects (detected by fMRI) have been reported [69]. A number of studies have demonstrated crossmodal recruitment of auditory areas in deaf individuals viewing sign language [70–72]. Visual crossmodal activation of auditory cortex has also been demonstrated using non-linguistic visual stimuli (e.g. moving dot patterns) using MEG [73] and fMRI [74] imaging methodologies. Interestingly, this same pattern of activation was not evident in hearing signers (specifically, the children of deaf parents) suggesting that auditory deprivation (as opposed to sign language experience) might be crucial for the observation of this form of crossmodal recruitment (see also [67] and text box 1 for further discussion). Finally, a series of neuroimaging studies combined with visual peripheral tasks have also reported findings consistent with the notion that deaf individuals show greater recruitment of occipital-parietal cortical areas related to attention processing compared with hearing controls [61, 63, 75, 76].

Establishing a causal role for the crossmodal recruitment of auditory cortex in non-auditory tasks has been less evident through experimental manipulation. This may be related to technical issues related to the experimental methodologies used. For example, TMS must be delivered in proximity to the ear itself to transiently disrupt the function of auditory temporal regions and the audible “click” sound generated with a discharging TMS coil may potentially interfere with task performance. Furthermore, apart from being relatively uncomfortable (due to stimulation of the overlying temporalis muscle), the sulcal geometry and orientation of auditory cortical areas make them difficult to stimulate optimally.

Although these aforementioned technical issues may have limited controlled experimental investigations, a number of case reports describing deaf patients with circumscribed brain lesions have provided some interesting clinical evidence regarding sign language production and comprehension. For example, lesions implicating left temporal cortical areas lead to impairments consistent with the notion that sign language comprehension depends primarily on left hemispheric structures as in the case of language function in hearing subjects [77, 78]. There have also been reports of “sign blindness” in a deaf signer following damage to the left occipital cortex [79]. This patient exhibited severe impairments in comprehension but not production of signs analogous to alexia. Similarly, a more recent report described a deaf signer with acquired sign-language aphasia with severe impairment in word production as well as comprehension, reading and writing due a left occipital lesion [80]. Thus, consistent

with neuroimaging data, it seems that temporal-auditory and occipital-visual cortical areas have specialized functions that are crucial for language abilities in deaf signers.

The adaptation to multiple sensory loss

The case of deaf-blind

Very few studies have examined the behavioural and physiological consequences of multiple sensory loss, particularly in humans. The development of language function and communication skills in deaf-blind individuals provides for an interesting opportunity to investigate this issue. Deaf-blind individuals rely on a battery of tactile-based languages for communication including Braille and various haptic forms of sign language. In a study of one late blind, post-lingual deaf-blind subject, MEG and positronic emission tomography (PET) imaging were used to investigate the neural correlates associated with identifying Japanese words using a tactile mode of letter spelling (i.e. by touching and stroking the fingertips representing different consonants and vowels) [80]. In line with the crossmodal changes described in visual and auditory deprivation, the identification of tactile presented words was associated with activation of visual and auditory language cortical areas. The results of this study suggest that in the case of dual sensory deprivation, dramatic crossmodal recruitment of cortical areas associated with visual, auditory and language processing is possible. In this latter study however, it is important to note that the subject's late blind and post-lingual deaf status makes it difficult to disentangle the contribution of prior sensory experience with regards to the pattern of crossmodal cortical recruitment observed. Indeed, both visual imagery [81] and inner speech and auditory verbal imagery [82] are both known to activate corresponding areas of occipital, auditory and language processing areas. To rule out this possible confound, the neural correlates associated with language processing in a congenitally deaf and early blind individual who is highly proficient in communicating through a haptic form of American Sign Language (ASL), were explored[83]. By placing his hand over a signer's hand, he is able to capture the meaning of words signs and gestures. Using fMRI, a robust activation associated with the identification of words (contrasted to non-words) within occipital cortex (including calcarine-striate and extrastriate regions), left-lateralized activation within posterior superior-temporal areas (including Wernicke's area and superior temporal gyrus; BA 22) and activation of inferior frontal cortical areas (including Broca's area; BA 44) were reported (figure 2 A). To further distinguish between activation related to haptic language processing and areas related to combined early onset deprivation, a control experiment used the same word identification task in a normally hearing and sighted interpreter for the deaf-blind. As with the deaf-blind subject, the identification of words through haptic ASL was associated with left-lateralized activation of inferior frontal language areas (including Broca's area; BA 44). However, robust occipital cortex activation was not observed (figure 2 B) [83]. The dramatic pattern of crossmodal recruitment observed in this deaf-blind individual is striking given that he never developed articulated speech nor has he learned ASL through visual associations as is typically carried out by deaf signers. Furthermore, these results suggest that following early onset visual and auditory deprivation, tactile-based communication is associated with the recruitment of occipital and auditory cortical areas, further demonstrating the remarkable degree of neuroplastic change that follows sensory loss.

Underlying mechanisms

The exact mechanisms underlying crossmodal plasticity and the neural basis for behavioural compensation remain largely unknown. However, numerous animal studies have provided important insights based on physiological, behavioural and anatomical support (see also [2, 6, 84, 85] for review). Similar to the behavioural results described in blind humans, animal models of visual deprivation also show evidence of crossmodal compensatory

changes. For example, experimentally visual deprived cats [6, 86] and ferrets [87] posses superior sound localization abilities compared with normal control animals. At a neurophysiological level, single-unit recordings made within a multisensory region called the anterior ectosylvian cortex demonstrate that in visually deprived cats, cortical areas that are responsive to auditory stimuli expand significantly [88] and neurons in this region are more sharply tuned to auditory spatial location [89]. The development and maturation of multisensory circuits has been recently studied within the anterior ectosylvian sulcus (AES) of the cat. Results from these investigations confirm that the capacity for multisensory integration is rudimentary during early postnatal life, that it gradually develops over time and that it is highly influenced by timing and the animal's overall sensory experience [90, 91]. To better characterize the contribution of early visual sensory experience on cortical multisensory development, further work was carried out on dark-reared cats [92]. In these experiments, semichronic single-unit recordings (in an anesthetized preparation) were made at weekly intervals from birth until adulthood within the AES region. The results confirmed that visual deprivation (and visual–nonvisual multisensory experiences) had a dramatic effect on the integrative capabilities of multisensory neurons within AES. Specifically, there was a significant increase in the proportion of multisensory neurons modulated by a second sensory modality (figure 3 B). These results confirm that early deprivation has a significant impact and demonstrate how the senses interact to reflect specific features of an animal's environment and ultimately optimize adaptation to that environment [91].

Corollary studies regarding auditory cortical plasticity have also been carried out. These are not as extensive as those carried out within the visual and somatosensory systems, possibly due to technical challenges in developing appropriate animal models and controlled restricted environments (see [93] for review). The organization of auditory receptive fields and cortical mapping have been actively studied using various electrophysiological techniques (reviewed in [94]). In a series of studies using congenitally deaf cats as a model, the extent of crossmodal reorganization has also been investigated. Specifically, electrophysiological recordings within the primary auditory cortex (A1) of congenitally deaf cats have been carried out [95]. Despite using a large battery of visual and somatosensory stimuli, no crossmodally driven responses could be found in A1 [95] (though it is unclear if such responses exist in other auditory, higher-order, associative areas). The investigators of this study proposed that in the case of congenital deafness, the ability to learn and develop higher-order auditory representations is substantially affected in the absence of auditory experience and that very early onset auditory deprivation cannot be compensated by **top–down** influences arising from higher tier auditory and associative areas [96]. Thus, the degree of crossmodal plasticity may be related not only to the timing and profoundness of sensory deprivation, but also whether one considers primary or associative areas. Along these lines, there has been an interesting speculation that A1 may represent higher processing complexity than V1 (i.e. processing stimuli beyond simple feature detection) and would therefore be more analogous to higher order areas along the visual processing stream [97]. In other words, differences in the functional contribution of primary auditory and visual areas within the context of sensory deprivation might be based on their inherent abilities to retain their intrinsic processing in response to crossmodal influences from other sensory modalities.

One possible mechanism to explain the recruitment of cortical areas following sensory deprivation is through direct neural connections in relation to intact sensory areas. In support of this notion, anatomical studies in the cat [98] and non-human adult primates have demonstrated the existence of direct connections between auditory visual cortical areas [99, 100]. Interestingly, these anatomical studies have also suggested differential patterns in connectivity with regards to primary versus associative areas as well as central versus peripheral visual cortical representations (see [98]). In a more recent anatomical tracing study

(using the marmoset model), multiple heteromodal connections have been revealed linking unimodal sensory areas including visuo-somatosensory, visuo-auditory and somatosensory-auditory projections [101]. Furthermore, supportive electrophysiological evidence in monkeys confirm multisensory convergence at the neuronal level and within early stages of cortical sensory processing including auditory-visual convergence within early visual areas (i.e. V1) [102] and somatosensory-auditory interactions within a region caudal-medial to primary auditory cortex [103]. Given these connections exist in the intact adult brain, one possibility is that in the case of sensory deprivation, changes in relative connectivity between cortical areas might be more pronounced.

At present, it is unclear if these same connections and mechanisms underlie crossmodal neuroplastic changes observed in humans. However, one study has provided some evidence consistent with the notion of enhanced cortico-cortical inter-sensory interactions. Specifically, effective connectivity between somatosensory and visual cortical areas was demonstrated in early blind humans using a combined technique of TMS (used to stimulate primary somatosensory areas) and PET imaging (to visualize the effect of somatosensory stimulation within early visual cortical areas) [104]. Furthermore, evidence of functional crossmodal sensory processing, implicating occipital visual cortex in adult sighted subjects [57, 105] and rapid and reversible crossmodal recruitment of the occipital cortex, in response to sudden and complete visual deprivation in normal adult humans through experimental manipulation (i.e. prolonged blindfolding and sensory training) are consistent with the notion that existing connections can be unmasked as a response to sensory processing and afferent demand [106]. Thus, it is possible that the unmasking of preexisting connections and shifts in connectivity may underlie rapid, early plastic changes which can lead, if sustained and reinforced, to slower developing but more permanent structural changes, such as dendritic arborization, sprouting and growth with rewiring of connections [107].

Critical periods and adult plasticity: Is timing really everything?

Early pioneering work in sensory deprivation (e.g. [108]) has demonstrated that the brain is most receptive to change during an early period of post-natal life referred to as the critical period[109]. Critical periods are specific to sensory modality and function as well as a given species [109]. Furthermore, experimental evidence is consistent with the notion that the earlier the sensory loss, the more dramatic the neuroplastic effects observed [109]. In fact, many of the studies reporting superior behavioural performance and crossmodal neuroplastic changes have been carried out in congenital or early blind and deaf subjects (see text box 1). In the case of blindness, this notion has led some authors to suggest the existence of a precise critical period (around 14 [110] to 16 [111] years of age) beyond which functionally relevant crossmodal recruitment of occipital cortex (particularly, V1) does not occur, theoretically limiting the extent of potential adaptive compensatory behaviour. However, the current view regarding plasticity is not one of a finite window of opportunity, but rather one in which the brain retains a high level of neuroplasticity well into adulthood, although not necessarily identical or to the same degree of that of the young developing brain [107]. Admittedly, neuroplastic changes and associated behavioural gains in the case of late onset sensory deprivation are less clear and relatively few studies have sought to address this issue. In one study, the occipital activation related to a verb-generation task (using a Braille word presented cue) in both congenitally and late blind subjects was compared. It found that occipital cortex activation (including early visual areas) was evident in both study groups [34]. However, comparing the magnitude and spatial extent of the activation patterns within occipital cortex was consistent with the notion that congenitally blind individuals showed greater activity compared with late blind participants. [34]. In terms of compensatory behaviours in the auditory domain, enhanced auditory spatial abilities (e.g. peripheral sound

localization) have also been reported in subjects with late onset blindness compared with sighted controls [20, 112]. With regards to auditory deprivation, the effect of timing on the acquisition of language function through the use of a cochlear implant (CI) device provides parallel insight. Traditionally, language acquisition following implantation has been approached with the mantra of "the earlier the better" [113] and only feasible in post-lingual deaf patients. More recently, the indications for CI implantation have expanded to include pre-lingual deaf patients. With very intensive and rigorous training, improved language performance outcomes have been reported in these patients [114].

Work in animal models may help to uncover the potential underlying neuroplastic mechanisms and their relation to critical periods, learning and developmental experience. Analogous to the visual deprivation studies mentioned earlier, it has been shown that rearing infant rats in a low frequency-modulated noise environment leads to profound deficits within primary auditory cortex that endure throughout adulthood (specifically, with regards to the spatial and temporal selectivity of neurons) [115]. Intriguingly, it has also been shown that these deficits incurred during the critical period of development can be re-normalized in the adult through intensive training (e.g. perceptual learning tasks) [116]. Thus, the possibility of "re-opening" critical periods in the adult animal through intensive behavioural and perceptual training has important implications for the re-gaining of function in adults even after early onset sensory deprivation. Furthermore, given that typical aging trends suggest that individuals are more likely to acquire sensory loss with increasing age as opposed to early in life (see text box 1), the issue of neuroplasticity within the context of late onset sensory deprivation also deserves careful investigation.

Restoring sensory function: Is less really more?

Although crossmodal plasticity following sensory deprivation can translate into compensatory behavioural gains, it is important to realize that it cannot be viewed as universally adaptive and unintended consequences are possible. In fact, neuroplastic changes may potentially undermine the ability of reorganized cortex to perform its primary function, particularly within the context of rehabilitative training (e.g. learning to read Braille proficiently or other forms of language training). Take for example crossmodal changes in the case of blindness. It has been reported that proficient Braille readers who use multiple fingers to read text can mis-identify fingers and mis-localize tactile stimuli compared with sighted controls [117]. As another example, TMS delivered to the occipital cortex of blind proficient Braille readers can induce phantom tactile sensations at the finger tips [51, 118] as well as at the level of the tongue in users of certain tactile based SSDs [119]. Perhaps the most dramatic examples come from historic case studies of surgical sight restoration following long-term visual deprivation (see [120, 121]). In the case of patients with early onset blindness of treatable cause (e.g. cataract removal or corneal transplantation), restoring vision in adulthood reportedly leads to profound difficulties in various visual tasks, particularly those requiring the identification and recognition of objects through sight alone. These outcomes have largely been attributed to the notion that early visual deprivation has dramatic effects on the development of visual cortex and its ability to process complex visual information. However, recent and more comprehensive behavioural and neuroimaging studies have revealed that these preconceived notions are not as definitive as once thought (e.g.[122–125]). Specifically, results from sight restoration surgeries performed in adults with early onset blindness now suggest that visual areas that process different visual attributes may possess differential susceptibility to visual deprivation and ultimately, differential recovery rates. Furthermore, although patients may not demonstrate dramatic improvement in measured visual acuity following surgery, a person can improve in other aspects of visual perception, thus discounting the assumption that if acuity does not progress, then neither do other properties of visual function [126]. What these recent studies also reveal is that despite years of

early onset blindness, the brain retains an impressive capacity for visual learning. Furthermore, these observations may lead to novel strategies of visual rehabilitation leveraging crossmodal transfer of sensory information (e.g. registering the direction of motion signalled through touch with what is perceived through vision) or using one visual attribute to "bootstrap" and enhance the development of another (e.g. learning to perceive object form as defined by its motion) [124].

In the case of deafness, these individuals have often been characterized as more "distractible" and more easily distracted by irrelevant information occurring in the visual periphery compared with hearing peers (see [62, 127] for further discussion). Similar to the observations made in the blind, there may be trade-offs in terms of adaptive gains and maladaptive outcomes resulting from underlying crossmodal neuroplasticity following sensory deprivation. Detailed work on this issue has also been carried out with regards to hearing and language development in CI patients. For example, it has been shown that in profoundly deaf CI recipients, speech performance outcomes are worse in those patients whose levels of metabolic activity within auditory cortical areas showed near-normal resting levels (assessed with PET imaging) [128, 129]. This sustained metabolic activity (attributed to evolved crossmodal neuroplastic changes) can ultimately interfere with the ability to recover auditory processing function after implantation of a CI device. Certainly, the duration of auditory deprivation remains an important factor however, the results of this study highlight the importance of investigating underlying neuroplastic changes directly as potential predictors of rehabilitative and functional outcomes (see also [128]). As with the case of sight restoration, these results continue to raise questions as to how restored and intact sensory modalities interact following the restitution of sensory afferents. There is evidence that crossmodal interactions between auditory and visual related cortical areas tend to increase following CI implantation and furthermore, these interactions may actually serve to mutually reinforce one another [130]. Such language related crossmodal changes may allow for visual sign language to exploit existing connectivity between auditory cortex and neighbouring semantic and language processing areas. Interestingly, there is even evidence that some CI users can integrate congruent auditory and visual information better than hearing control subjects [131]. However, as mentioned earlier, these beneficial effects cannot be considered universal and there remains the possibility that under certain circumstances, these same crossmodal sensory interactions may prove to be intrusive. A recent study investigated this issue by assessing the ability to segregate conflicting auditory and visual information in an auditory speech recognition task [132]. Key to the study design was the fact that hearing control subjects were gender, age and hearing performance matched to CI patients. Impaired task performance was particularly evident when comparing non-proficient CI users to their hearing matched controls [132]. These findings highlight how functional reorganization following auditory reafferentation may be beneficial in certain cases, but detrimental to audiovisual performance in others, and may help to explain the dramatic variability in performance outcomes observed following CI implantation.

In summary, these reports of sensory restoration in both the blind and deaf highlight how evolving plastic changes may lead to a gradual deterioration in the ability to process the missing sense and potentially render an individual a poor candidate for procedures aimed at restoring the lost sensory function. Thus, the decision to implant a prosthetic device or implement a given rehabilitative strategy needs to consider not only its effects on residual sensory function but also the potential to interfere with evolving crossmodal processing in response to sensory loss [133].

Conclusions and the implications for rehabilitation

In light of the dramatic neuroplastic changes that follow sensory deprivation, it seems that compensatory behaviour is not so much the result of sensory deprivation alone, but rather the consequence of how the entire brain maintains function within the context of sensory deprivation [107].

As a result of sensory deprivation, some of these plastic changes lead to crucial functional advantages, such as enhanced localization of sound sources and improved verbal memory in the blind and enhanced visual peripheral sensitivity in the deaf. However, not all neuroplastic changes represent behavioural gains and the restoration of a deprived sense does not automatically translate to its eventual functional restitution. Neuroplasticity clearly affects an individual's rehabilitative outcome and novel strategies are needed to leverage cross-modal interactions in a manner that promotes functional adaptation in parallel to rehabilitative and restorative approaches. These will require a careful consideration of brain plasticity mechanisms, perhaps even modulating brain activity (such as with noninvasive brain stimulation combined with rehabilitation) on an individual basis to therapeutically guide synaptic plasticity mechanisms and enhance those that promote behavioural gains and suppress those that may be maladaptive [107, 134].

In conclusion, it is not possible to understand normal physiological function, the manifestations or consequences of sensory loss, or the possibility of resorting sensory function without incorporating the concept of brain plasticity. In considering the rehabilitation of an individual following sensory loss, it is crucial to consider each individual's specific needs and goals within the context of his or her plastic brain interacting within a multisensory world.

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Text Box 1: The heterogeneity of sensory loss: a potential confound

The world health organization (WHO) defines legal blindness as a best-corrected visual acuity worse than 20/200 (Snellen equivalent) or a visual field less than 20 degrees (note that legal blindness does not necessarily imply profound blindness). Current estimates suggest that blindness afflicts 45 million individuals worldwide with cataracts, age-related macular generation and glaucoma representing leading causes [135]. In terms of hearing impairment, the WHO has estimated that 278 million individuals worldwide have moderate to profound hearing loss in both ears (profound hearing loss being defined as not being able to detect a tone of 90 dB or greater) and causes are typically associated with sensorineural deficits of the auditory nerve [136]. As with visual impairment, the aetiology is highly variable and includes hereditary as well as acquired causes including infections and trauma. Combined vision and hearing loss (or "dual" sensory loss) is more prevalent with increasing age. However, certain hereditary conditions such as **Usher syndrome** [137] can also lead to combined early onset of visual and auditory impairment.

When interpreting the breadth of experimental evidence available, it is important to underscore the tremendous degree of heterogeneity with regards to sensory impairment in both blind and deaf populations. The aetiology of the sensory loss may represent an important factor as well as a multitude of other variables such as the severity, onset and developmental time course of the sensory impairment. Furthermore, it is worth noting that many of the human studies demonstrating superior performance abilities in blind and deaf have been carried out in highly specific population subsamples, such as in congenitally blind individuals or deaf native signers (i.e. children who have had early exposure to sign language and achieve language development milestones similar to hearing individuals, see [127]). Additionally, many of these studies have been carried out under very controlled experimental conditions and/or high task demands (e.g. monaural testing [18]) or by comparing performance against control subjects but under acute sensory deprivation conditions (e.g. blindfolding sighted participants [12]). As a further confound, careful experiments need to be designed to disentangle evidence of brain activation related to long-term skill training (eg. Braille and ASL) versus activation due to the sensory deprivation itself (see[56, 67, 73, 138]).

At the other extreme, studying specialized population subgroups and highly controlled experimental conditions may allow for 'cleaner' interpretation of data but potentially at the expense of a loss in generalizabilty across the entire population. Finally, vision and hearing loss typically occur progressively, later in adult life, and individuals often maintain some degree of residual sensory function. Future studies may benefit from considering variables beyond simply the aetiology and strict age cut-offs for acquiring total sensory deprivation. For example, functional (e.g. language experience and travel independence), personal (e.g. confidence and motivation) and behavioural (e.g. degree of instruction and level of proficiency) criteria may prove helpful in grouping and comparing study subjects in terms of underlying neuroplastic change (see also [62, 127, 139] for related discussion).

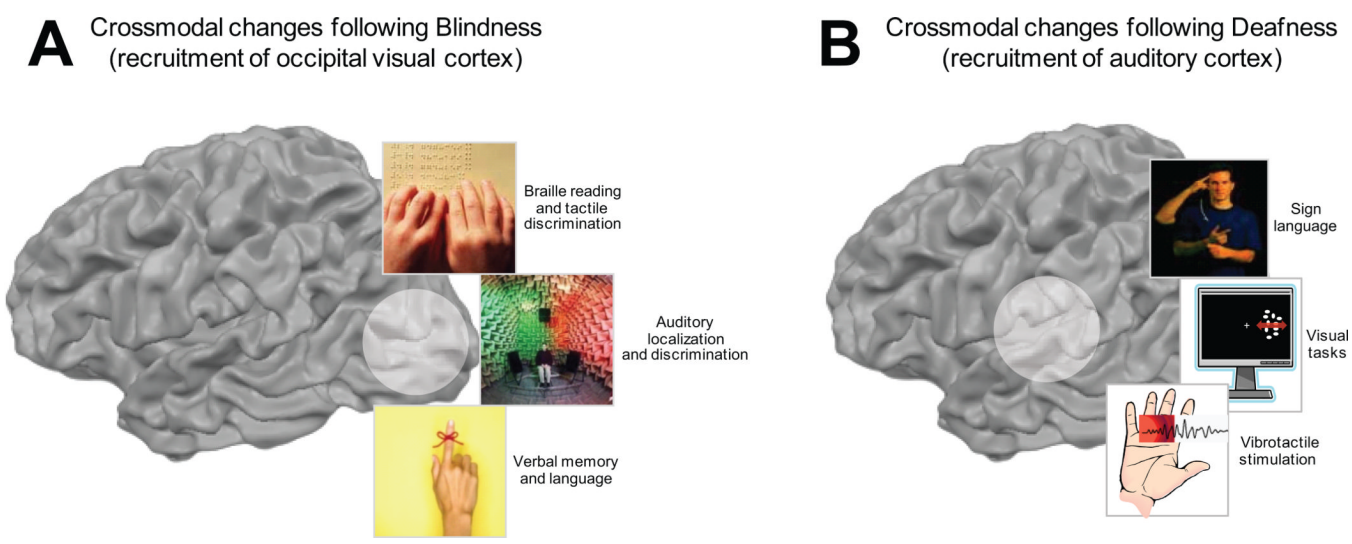

Figure 1. Summary of crossmodal neuroplasticity changes following sensory loss

Crossmodal recruitment of occipital visual cortex in the blind and auditory cortex in the deaf have been reported. (A) Occipital recruitment for tactile processing such as Braille reading, sound localization and verbal memory. (B) Recruitment of auditory and language-related areas for viewing sign language, peripheral visual processing and vibro-tactile stimulation.

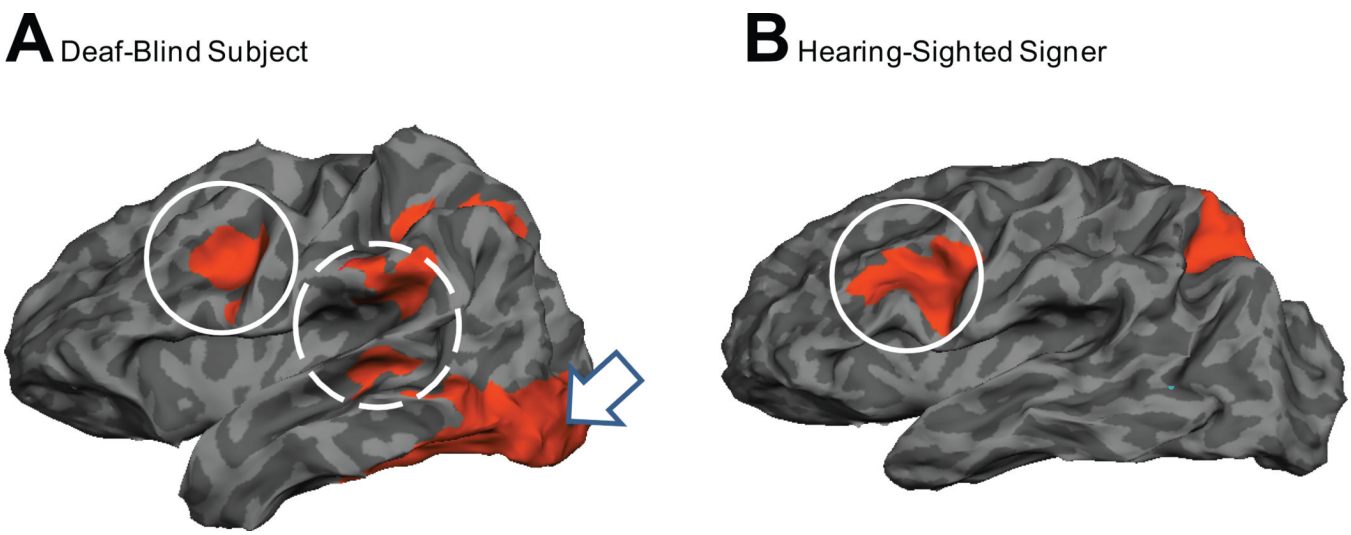

Figure 2. Crossmodal neuroplasticity changes in the case of dual sensory loss (vision and hearing)

Localization of activation (revealed by fMRI) associated with identifying words through haptically presented American Sign Language (ASL) in both a prelingually deaf and early blind (A) and a hearing-sighted control (B) subject (for simplicity, only the left hemisphere is shown). Crossmodal networks associated with the identification of words (contrasted to non-words) include inferior frontal cortex activation within the left hemisphere (corresponding to Broca's area, BA 44) in both subjects (white circle). The white dashed circle identifies activation within superior temporal language areas (including Wernicke's area and superior temporal gyrus). The arrow indicates occipital cortex activation. Activation within occipital and temporal cortical areas seem to be specific to the combined loss of vision and hearing.

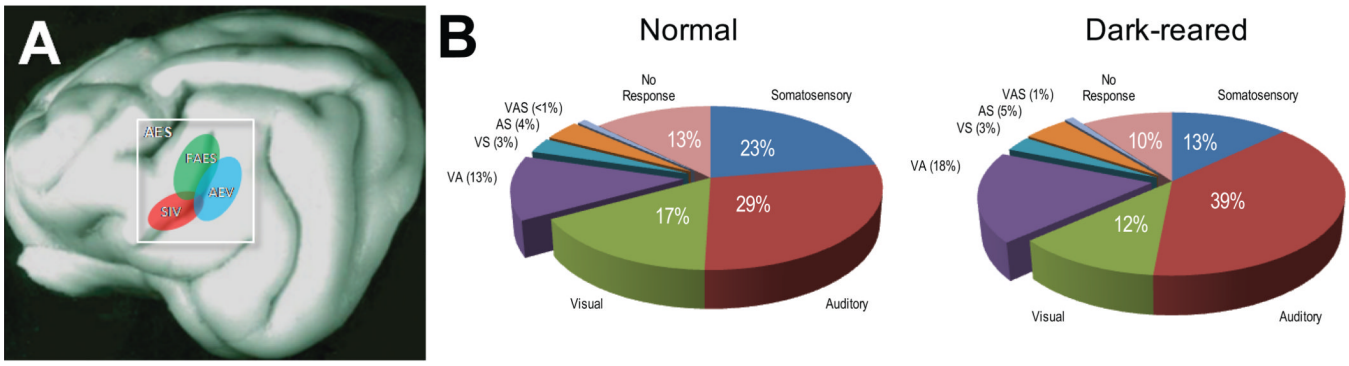

Figure 3. Effects of early visual deprivation in cats

Dark-rearing alters the distribution of sensory responsive neurons in the anterior ectosylvian sulcus (AES). A. Schematic drawing of the lateral surface of the adult cat cortex showing the location of the AES and the relative position of its three major subdivisions: SIV (fourth somatosensory area), FAES (auditory field of the AES) and AEV (anterior ectosylvian visual area). B. Distribution of sensory unresponsive, unisensory and multisensory mature AES neurons in normally reared and dark-reared animals. Abbreviations: VA, visual auditory; VS, visual somatosensory; AS, auditory-somatosensory; VAS, visual-auditory-somatosensory. Part A modified from [2]. Part B data from reference [92].