DO VISUAL CORTICES IN THE BLIND ACTIVATE TO LANGUAGE PROCESSING DEMANDS?

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We certify that we have read this thesis and that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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ABSTRACT

DO VISUAL CORTICES IN THE BLIND ACTIVATE TO LANGUAGE PROCESSING DEMANDS?

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The fate of the occipital cortices in the blind has been of considerable interest in neuroscience to investigate whether and how much brain regions change with experience. Neuroimaging shows that the occipital cortices in the blind are activated during all kinds of non-visual tasks. In our previous study, we recently showed that all visual regions become MD regions and activate in response to any kind of control demand in the blind. Therefore, we hypothesized that the activation of the deprived visual cortex in language tasks in the literature is related to high cognitive control demand rather than language processing. This means that if V1 is involved in cognitive control demand, then it should not be activated in the passive listening task. Therefore, the study investigates whether the primary visual cortex (V1) in blind subjects participates in cognitive functions, particularly language processing, during a passive listening task with minimal cognitive control demand. Using fMRI, we compared whole brain and region of interest (ROI) activations in blind, and sighted participants across multiple areas, including occipital, language, and multiple demand (MD) regions. Results revealed no significant activation in V1 across all groups during the passive listening task, suggesting task-dependent limitations in the integration of V1 into higher-order cognitive processes rather than language. Furthermore, no significant differences in language or MD area activity were observed between blind and sighted participants. These findings challenge previous evidence on the occipital cortex becoming a language region in the blind and emphasize the importance of task complexity in modulating such interpretation. All of these suggest that blind occipital regions primarily become MD regions, and their activation during language tasks is limited to those that require domain-general cognitive control.

Keywords: neuroplasticity, blind, language regions, multiple demand regions.

ÖZET

KÖRLERDE GÖRSEL KORTEKSLER DİL IŞLEME TALEPLERİNE GÖRE AKTİVE OLUR MU?

Ayşe Betül Varol
Nörobilim, Yüksek Lisans
Tez Danışmanı: Ausaf Ahmed Farooqui
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Körlerde oksipital kortekslerin kaderi, beyin bölgelerinin deneyimle değişip değişmediğini ve ne kadar değiştiğini araştırmak için sinirbilimde önemli bir ilgi alanı olmuştur. Nörogörüntüleme, körlerde oksipital kortekslerin görsel olmayan her türlü görev sırasında aktive olduğunu göstermektedir. Daha önceki çalışmamızda, tüm görsel bölgelerin çoklu talep bölgeleri haline geldiğini ve körlerde her türlü kontrol talebine yanıt olarak aktive olduğunu göstermiştik. Bu nedenle, literatürdeki dil görevlerinde yoksun görsel korteksin aktivasyonunun dil işlemeden ziyade yüksek bilişsel kontrol talebiyle ilişkili olduğunu varsaydık. Bu da, eğer birincil görsel korteks (V1) bilişsel kontrol talebinde rol alıyorsa, pasif dinleme görevinde aktive olmaması gerektiği anlamına gelmektedir. Bu nedenle, bu çalışma kör katılımcılardaki birincil görsel korteksin, minimum bilişsel kontrol talebi olan pasif bir dinleme görevi sırasında bilişsel işlevlere, özellikle de dil işlemeye katılıp katılmadığını araştırmaktadır. fMRI kullanarak, kör ve gören katılımcılardaki tüm beyin ve ilgi bölgeleri aktivasyonlarını oksipital, dil ve çoklu talep bölgeleri dahil olmak üzere karşılaştırdık. Sonuçlar, pasif dinleme görevi sırasında tüm gruplar arasında V1'de geçerli bir aktivasyon olmadığını ortaya koymuştur; bu da V1'in dilden ziyade daha üst düzey bilişsel süreçlere entegrasyonunda göreve bağlı sınırlamalar olduğunu düşündürmektedir. Ayrıca, kör ve gören katılımcılar arasında dil veya çoklu talep bölgeleri aktivasyonunda önemli bir farklılık gözlenmemiştir. Bu bulgular, oksipital korteksin körlerde bir dil bölgesi haline geldiğine dair önceki kanıtlara meydan okumakta ve bu tür bir yorumlamanın modüle edilmesinde görev karmaşıklığının önemini vurgulamaktadır. Tüm bunlar, kör katılımcılardaki oksipital bölgelerin öncelikle çoklu talep bölgeleri haline geldiğini ve dil görevleri sırasında bu bölgelerde görülen aktivasyonun, yalnızca alan-genel bilişsel kontrol gerektiren görevlerle sınırlı olduğunu göstermektedir.

Anahtar sözcükler: nöroplastisite, kör, dil bölgeleri, çoklu talep bölgeleri.

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I am so proud to be your daughter. You all are my constant source of strength and hope. Your daughter has made it, and I owe it all to you.

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Chapter 1

Introduction

The functioning of specific brain regions and their roles are relatively well-known findings in neuroscience. Over the years, research has been driven by these well-established findings, but new findings have led us to question this acquired knowledge and gain new perspectives. One of these is the flexible nature of the brain.

The plasticity of the brain is one of the most remarkable discoveries. It refers to the ability to reorganize and reuse regions in response to brain damage, sensory loss, or changes in experience [3]. This ability has shown itself in many different ways, enabling research to progress on this subject. Some studies have claimed that brain regions do not change [4] or that the change is limited rather than categorical [5]. However, in addition to these findings, examining individuals who have recovered complex functions despite significant brain changes [6] and even in cats following brain trauma, the remaining areas replaced the injured areas [7] . These contradictory findings have raised questions about the underlying mechanisms that make it possible for cognitive functions to persist or adapt. Understanding that brain organization may be more adaptive based on the likelihood of significant changes in structure may point to a more dynamic view of brain function that can account for both stability and flexibility in understanding cognitive processes.

1.1 Neuroplasticity

Building on this perspective, neuroplasticity research has challenged our traditional understanding of fixed localization of brain by showing that people regain cognitive function after significant brain damage and even retain language function despite the removal of the language-dominant hemisphere [8]. Rarely, large brain lesions have been found incidentally during neuroimaging or autopsy in individuals who have lived or are living an everyday, healthy life [9], [10]. In the case of hemispherectomy, the remaining half is organized in the same way as in controls, meaning it is composed of the same networks and has the same relationships with and between them [11].

These findings highlight the brain's striking neurosensory plasticity and show that brain regions are not as rigidly specialized as once thought [12]. This has raised important questions about whether the brain can change and, if so, how much. Although most cases of neuroplasticity are related to brain damage, similar patterns are observed in blind individuals [13], [14]. The issue of neuroplasticity in this group still needs extensive research, and its conditions and limits still need to be fully understood. Therefore, due to the structure of the sensory cortices, the functional reorganization of these related regions in their absence provides an accessible method for understanding plasticity [15], [16] in comparison to other brain regions.

1.2 Primary Sensory Cortices

Primary sensory cortices, such as the visual cortex (V1), auditory cortex (A1), somatosensory cortex (S1), and other primary sensory cortices, are the first areas in which all types of sensory information are processed [17], [18], [19]. These areas are the first cortical regions to receive sensory input [18]. Since the information in the pathways through which sensory information flows is better mapped and understood than in other parts of the brain [18], this makes primary sensory

cortices an apt choice for investigating how input changes can lead to structural and functional adaptations [20]. For instance, the primary visual cortex is dedicated to processing visual information sent from the retina via the optic nerve and thalamic lateral geniculate nucleus (LGN) [21]. The visual pathway provides a straightforward channel for V1 to enter higher-level visual processing regions.

In detail, the primary visual cortex is distinguished by their six layers architecture. Each layer has a different function in transmitting and processing sensory data. For example, the thalamus's lateral geniculate nucleus (LGN), which transmits visual information from the retina to V1, provides direct input to layer IV. After undergoing additional processing at different levels of V1, sensory inputs are routed to higher-level visual centers for more complex interpretation [18]. This layered and topographical organization allows the primary sensory cortices to be highly specialized compared to other brain regions. Thus, V1 is optimized for essential visual elements such as edges, contrasts, and orientations; A1 is specialized for identifying different sound frequencies; and S1 is specialized for perceiving small tactile details such as pressure, texture, and vibration. This division of labor in the brain enables sensory information to be processed efficiently and precisely, may lead for more advanced perceptual and cognitive abilities. Given this information, V1 has been extensively studied because of its well-mapped structure and important function in integrating and transmitting visual information compared to other brain regions. This methodological arrangement allows researchers to see how the functional organization and connectivity of V1 are affected by changes in visual input resulting from injury, or sensory loss [22], [23]. In light of this information, the V1 region stands out as a critical region for understanding how loss of sensory input leads to neuroplastic changes.

Considering their structure, one could anticipate that these key sensory circuits would only function when handling the inputs that correspond to these senses. However, studies have demonstrated that sensory cortices are not limited to their typical sensory functions. For instance, blind people's visual cortex can be triggered to interpret auditory and tactile information [3], [13]. This makes it possible for neurons in the region to be recruited for non-visual functions, including cognitive control, and to adapt to sensory loss [24]. These findings challenge the

traditional view that sensory cortices are strictly limited to processing modality-specific inputs (e.g., visual inputs in the case of the primary visual cortex, V1). For example, studies have shown that V1 is typically dedicated to processing visual stimuli while indicating that it can be actively integrated into larger neural networks that support higher-level cognitive activities such as language and memory [25].

1.3 Sensory Neuroplasticity

This integration capacity, sensory plasticity, covers various adaptive processes by which the brain reorganizes itself in response to sensory loss, injury, or environmental changes. One such mechanism is cortical reorganization, which involves changes in the representation of sensory input within primary sensory cortices. For example, after limb amputation, the somatosensory cortex reorganizes, allowing neighboring cortical areas to process information from other body parts [26]. Investigating how spinal cord injury affects the functional architecture of the primary somatosensory cortex reveals significant changes in cortical activity patterns, showing that areas of the primary somatosensory cortex previously responsible for processing input from the affected body parts are reassigned to adjacent regions [27]. However, this brain flexibility should not be thought to be seen only in the face of disease. Studies have shown that professional athletes and musicians exhibit functional adaptations in their sensory cortex outside of visual inputs [28]. This situation has shown that neuroplasticity is not limited to the patient population and is also related to skill development in sensory-intensive tasks. Sensory neuroplasticity also highlights the importance of age in such adaptations. Research in this area argues that children exhibit more extensive sensory plasticity and reorganization than adults because their brains development strınger than adults, which has important implications for early intervention in such situations [29]. This reorganization under different conditions and situations involved in sensory neuroplasticity highlights the brain's extraordinary ability to adapt to sensory loss. Although reorganization can take many forms, since we are focusing here on the neuroplasticity of sensory cortices, we will continue to refer to the

loss of primary sensory cortex as deprived sensory cortex.

1.4 Deprived Primary Sensory Cortex in Blind

A deprived sensory cortex is a primary sensory region of the brain that lacks its typical sensory input due to sensory loss, such as blindness. For example, in blind individuals, the primary visual cortex (V1), which typically processes visual input, is deprived of such input due to the absence of visual sensory signals. Despite this, these cortices do not remain inactive; they can reorganize and adapt to process other types of input or support higher cognitive functions through sensory neuroplasticity [3], [30]. This adaptability highlights essential information about neuroplasticity and how the brain adapts to sensory loss due to its functions. Sensory neuroplasticity describes the restructuring of the visual cortex, as a consequence of these changes. This reassignment occurs because these cortices have a strong motivation to take on different tasks when inputs are missing. For example, tactile exploration is a non-visual process that activates the visual cortex in blind individuals [13]. Braille reading [13], manipulating objects [31], and even olfactory tasks activate these areas in blind people [32], [33]. Additionally, in tactile discrimination tests, blind individuals performing fine-grained spatial tasks may experience flexible reorganization of the occipital cortex that enhances tactile sensitivity and spatial processing [34]. Also, intense activation has been reported in the occipital cortex of visually impaired participants during verb production in response to auditorily presented nouns [35], verbal memory [25]. There are also findings that the occipital cortex is activated in language comprehension and generation [24], even in blind children to spoken language [36]. Furthermore, in blind individuals, the occipital cortex is also involved in numerical and mathematical processing tasks [37]. This suggests that deprived sensory cortices may support abstract cognitive functions, adapting to the process of cognitively complex information. [38] have shown that blind individuals exhibit occipital activation in verbal memory tasks. In addition to these, the deprived occipital cortex can integrate information from different sensory inputs into a joint cognitive framework [39].

These deprived visual cortex samples not only emphasize the adaptive potential of sensory cortices but also show a major degree of cognitive integration into the brain's organizational framework, underlining the importance of neuroplasticity studies in this domain. Therefore, it is also important to understand the interpretation of these findings according to different existing accounts.

1.5 Current Explanations of Findings Related to Deprived Visual Cortex

1.5.1 Cross Modal

One of the alternative perspectives that these findings can consider is the cross-modal account. As we mentioned, the ability to reorganize sensory processing areas to take on functions of a deprived sensory modality [14], such as in the case of blind individuals whose visual cortex activity aids their tactile or auditory processing [40]. This suggests that this visual cortex becomes another region, as the auditory cortex activates the occipital cortex in blind individuals [41]. Similar research revealed that in the case of spatial sound processing again, the occipital cortex in the blind is involved in such a task [42]. Recent findings have also demonstrated the timelines of this phenomenon, suggesting that this adaptation of the brain continues throughout adulthood [43]. This highlights that the brain's functional organization is dynamic and can reorganize itself following sensory loss.

1.5.2 Meta Modal

In another account of the results, meta-modal suggests that these regions do not become other regions but specific brain regions that process sensory information flexibly across modalities, such as the occipital cortex's ability to process non-visual inputs. As in, the posterior parietal cortex might integrate visual and tactile information in order to support reaching or navigating through space [44].

In other words, it plays a role in processing cognitive tasks, no matter what type of sensory input is involved [45]. In summary, meta-modal flexibility highlights how deprived sensory cortices reorganize to support nonsensory cognitive functions. Thus, meta-modal flexibility may extend to support memory functions and add another dimension to the brain's adaptive capabilities in sensory-deprived contexts.

1.5.3 Supra Modal

On the other hand, the supra-modal account interprets those existing results as such adaptations are not exclusive to deprived groups, can be seen in sighted people as well [46]. So, according to the supra-modal account, these are not modality-specific to begin with. Overall, it offers a different perspective on the brain, helping us understand how it maintains functional coherence across sensory modalities and contributes to advanced cognitive processes relying on unified sensory perception.

1.5.4 Pluripotent Cortex

The pluripotent cortex offers a different perspective on these modalities, which refers to specific regions of the brain that have the natural plasticity to take on new functions in the absence of sensory inputs. In order to process different types of sensory information in the absence of these typical inputs, such as the visual cortex [47]. One study that emphasizes the pluripotent cortex has shown that the occipital cortex can be activated during complex verbal memory tasks. Deprived cortical areas are not limited to sensory reorganization but can also support abstract functions that often rely on other brain networks [38]. Another evidence showed that the occipital cortex in blind people supports auditory spatial processing and highlights its role in developing spatial awareness. [48]. This finding again highlights that the brain's potential for neuroplasticity extends beyond sensory shift and traditionally adapts the visual cortex to engage in complex spatial

and cognitive tasks.

Plasticity mechanisms in the pluripotent cortex enable these sensory regions to be 'recruited' for various sensory or cognitive tasks in sensory-deprived individuals. This adaptability demonstrates the brain's multifunctional structure, enabling cortical regions to take on new roles when necessary to compensate for deprived sensory inputs. These findings reveal an important reconfiguration between the deprived sensory cortices and other sensory networks. They conclude that sensory cortices do not entirely depend on one function but integrate with other sensory systems to fulfill functional needs, illustrating their flexible role in cognition and cognitive control.

1.6 Cognitive Control

Cognitive control is the brain's ability to manage thoughts and behaviors according to goals or demands [49]. This ability focuses on adaptive behavior, attention shifting, and focusing, including suppressing distractions and applying and using learned information according to context [50]. It is responsible for planning, decision-making, and task-switching [51]. Neuroimaging studies have revealed the relationship between brain regions and cognitive control; cognitive control involves the prefrontal cortex that integrates sensory and motor information to facilitate goal-directed behavior and coordinates actions across multiple neural regions [52]). Regions such as prefrontal cortex, and the anterior cingulate cortex (ACC) plays an important role in prioritizing, sequencing, and managing competing demands [53]. As another example, studies suggest that the parietal cortex may contribute to cognitive switches, providing task flexibility and response inhibition across different cognitive demands [54]. Thus, based on these examples, other brain regions may also make specific contributions to cognitive control. In addition to connectivity between brain regions, cognitive control also benefits from the frontoparietal network, includes the dorsolateral prefrontal cortex (DLPFC) and posterior parietal cortex (PPC). These has an important role in managing transitions between intensive cognitive tasks [55]. This harmony is

crucial for completing complex or multi-step tasks (e.g., preparing food involving sequential steps up to a certain time) or problem-solving situations. This emphasizes that complex tasks rely on a coordinated network of brain regions that support cognitive control.

That is, cognitive control is involved in higher-order processes with an important component that enables these functions to be managed and directed. At this point, the findings indicates these may be integrated into broader cognitive systems, such as the multiple demand (MD) network. It is responsible for a range of higher-order cognitive functions such as attention, problem-solving, and working memory [56].

1.7 Multiple Demand Regions

The MD regions are frontoparietal regions that activate in response to any task-relevant event and all types of control demand, regardless of the sensory modality involved. It involves various cognitively demanding tasks such as problem-solving, attention, cognitive control, neural network, and goal-directed behavior in executive functioning [57], [56], [58], [59]. It consists of areas such as the dorsolateral prefrontal cortex, the inferior parietal lobule, and parts of the anterior cingulate cortex [56].

Importantly, these fronto-parietal regions associated with control diverge significantly from primary sensory regions. The function of this region has been described as a comprehensive workspace due to the maintenance of information from different sensory and cognitive systems [56]. Activation in these regions, associated with rule enforcement requirements, cognitive control demands, such as how much attention the event requires, how much task-relevant information must be maintained, and how much of the limited capacity of cognitive resources is consumed by the event [56], [52]. Therefore, the same regions are more active during increased attention to visual, auditory, or tactile information. Moreover, research shows that beyond these processes, MD regions are also active in new or

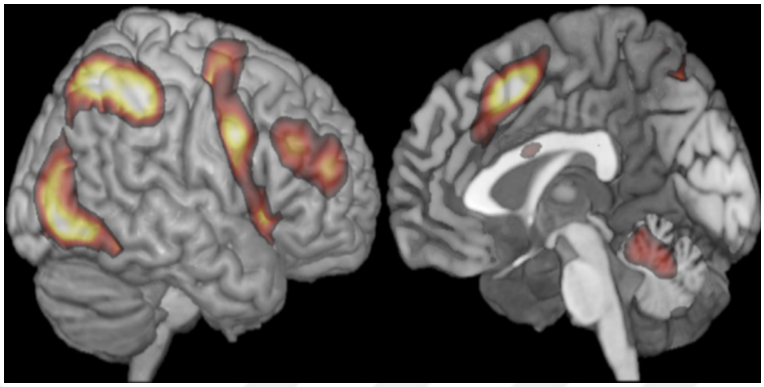

Figure 1.1: A common set of fronto-parietal regions is active across diverse task blocks and in response to all kinds of control demands. (Reproduced from [1] with permission).

unpredictable situations where flexibility is essential [60] such as requiring memory, problem solving [61], [62]. This adaptation reflects the role of the MD region as a core system for cognitive control while also providing importance of process tasks that vary greatly depending on the situation and share the demand for focused.

Overall, previous studies have shown that deprived visual cortices in congenitally blind individuals are activated during tasks requiring higher cognitive functions such as working memory, response inhibition, episodic memory recall, and mathematical operations [24], [25], [63]. Furthermore, given that the multiple demand (MD) networks are involved in a variety of cognitively demanding tasks, it is possible that the primary visual cortex may not function solely as a sensory area but instead be integrated into domain-general cognitive processes based on accounts of sensory neuroplasticity and the flexible nature of the MD network.

1.8 Reassessing Existing Findings

In this regard, our previous work has shown that deprived sensory regions in the blind may be integrated into the multiple demand (MD) network, which supports the idea that the deprived sensory cortices studied in the blind show all the key

features of MD regions, i.e., activation of the same foci in response to various control demands. In addition to fronto-parietal MD regions, the entire occipital cortex in the blind group was activated in response to various control demands and was functionally connected to MD regions [2]. This leads us to reevaluate existing studies by bringing an alternative perspective to previous findings in the literature.

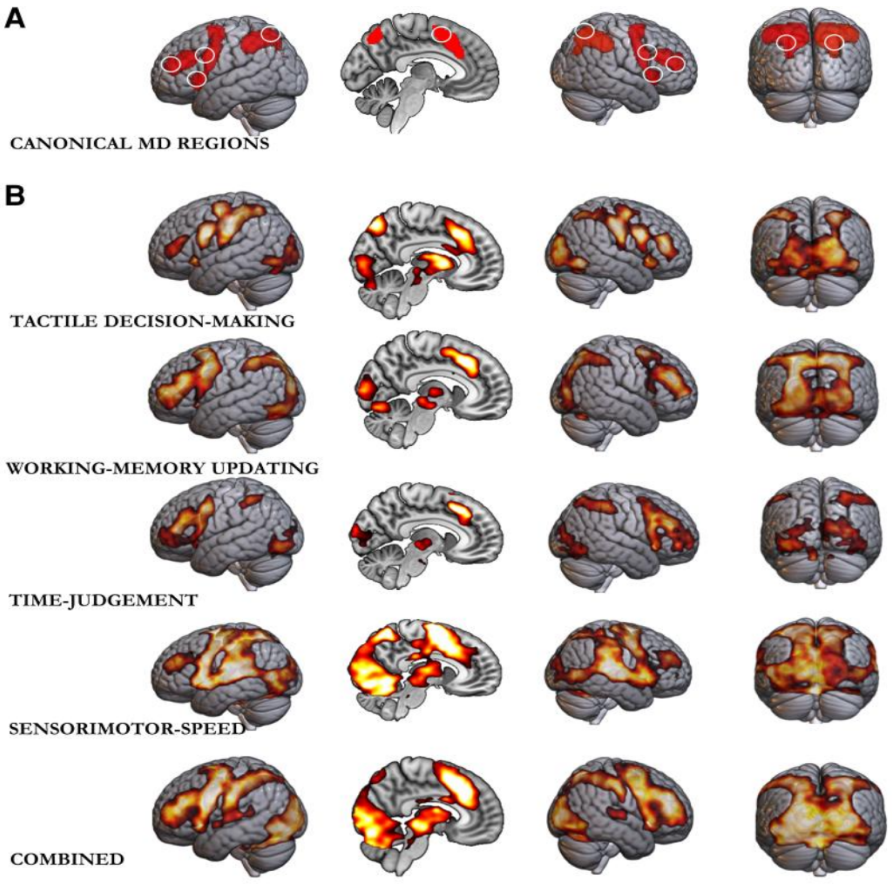

Figure 1.2: MD regions and whole-brain activation in the blind different cognitive demand tasks (Reproduced from our previous work, [2])

1.8.1 All Occipital Regions in the Blind are MD Regions

As mentioned above, all visual regions in blind people became MD regions [2]. This adaptation highlights the neuroplasticity of the visual cortex in higher-level

cognitive tasks, which are traditionally specialized for visual processing. In particular, the involvement of areas outside the primary visual cortex in the occipital cortex (e.g., V2, V3) reinforces that this adaptation involves a broader network. Deprived visual regions were recruited to support roles such as attention, working memory, and problem-solving. This demonstrates the flexibility of an MD network in response to changing sensory input.

This reorganization suggests that cross-modality may enable sensory cortices to be redesigned to meet cognitive demand needs. That is, this sensory region extends beyond sensory processing to higher-level cognitive processes. These visual regions that become MD regions are domain-general. Their activation is linked to task complexity and cognitive control requirements such as attention, working memory, or decision-making. However, in the absence of such demands, especially during passive sensory stimulation, these regions remain inactive. Notably, they are not activated in response to passive sensory stimulation [64].

1.8.2 What About Language findings?

In blind individuals, in particular, deprived sensory cortices exhibit a remarkable ability to support language functions. For example, regions within the occipital cortex have been shown to be activated during linguistic tasks, including syntactic processing, and to emphasize the transition from visual to linguistic functions in the absence of vision [41] and verbal processing [65]. They argue for the adaptability of the brain by integrating deprived sensory cortices into larger neural networks. Hence, sensory regions can adapt and contribute to higher-level tasks, including those related to language.

This highlights a network-level reorganization, such as an MD network that extends beyond the occipital cortex. The fact that our previous research uncovered this finding led us to critically re-evaluate the existing literature on language processing to better understand these interconnected mechanisms. However, although some studies have shown that visual regions are activated during language tasks in the blind, this issue should be carefully analyzed under language.

1.9 Language-Related Activations in Deprived Visual Cortex

It has already been stated that the brain's remarkable ability to adapt to sensory loss. It has provided important insights into the plasticity of cortical functions, as well as in language processing. Traditionally, language processing has been thought to rely primarily on regions such as Broca's and Wernicke's areas, the middle and inferior temporal gyrus, and the angular gyrus [66], [67], [68], [69]. However, recent research suggests language processing goes beyond these core regions and involves larger, interconnected networks [70], [60]. These cortices may participate in language-related functions like traditional language regions in the fronto-temporal lobes and integrate primary language areas with other domain-general regions, enabling the brain to support various aspects of language comprehension and production [71]. For example, [72] emphasizes the critical role of these networks in integrating syntax, semantics, and working memory during complex linguistic tasks. This language network, which includes primary language regions and other areas that support or regulate language functions such as attention, memory, and sensory integration, is called the language network [73]. In the case of blind people and their visual cortex, research has indicated that the language network may include certain visual regions [24], [41]. For instance, a study on people with bilateral anophthalmia demonstrated that the brain can repurpose the occipital cortex, devoid of visual input from birth, for higher-level language functions, and this region is activated during auditory naming and language tasks [24]. The idea that these regions are capable of doing intricate non-sensory tasks is supported by this reconfiguration, which emphasizes how the blind person's deprived visual cortex has adapted for language processing. In other words, they claimed that the visual cortex in blind people develops into an area with multiple functions used for a range of sensory, cognitive, and language tasks functions. Notably, these studies often included tasks with significant domain-general demands that also tend to activate MD regions.

1.9.1 Language Network and MD Regions

In this regard, research revealed that language tasks that have a higher component of domain-general control demands do activate MD regions [60]. However, these activations are not related to linguistic demands but rather separate [74]. [75] further demonstrated a correlation between increased activation in the MD network and higher cognitive control requirements in language processing, such as resolving syntactic ambiguities or making sophisticated semantic judgments. It is crucial to distinguish these activations from those directly related to language functions.

As in the case of domain-general areas such as the dorsolateral prefrontal cortex and intraparietal sulcus support cognitive control during language tasks but are not directly involved in basic processes of language such as syntactic and semantic processing according to numerous studies [60], [76]. Another research indicated, in the case of arithmetic or problem-solving, [77] showed that MD areas respond to task difficulty in various areas and that the reason these regions are activated to difficult language tasks is not the linguistic content itself, but rather the increased control demands. As [76] suggested, the MD network is only involved in language comprehension under certain conditions, mainly when the language network is inadequate or when cognitive demands are high. On the contrary, another study claimed that in blind people, a subset of visual areas are specialized for language processing, and they found that these same visual areas respond to a quite specific language-syntactic movement, which plays a key role in determining functional specialization [78]. This difference emphasizes that MD area activations during language tasks are more indicative of the cognitive demands of organizing information or sustaining attention, meaning these studies have executive demands hidden in them rather than being influenced by linguistic characteristics.

1.10 Reassessing Language Findings in Blind

While it is clear that they assist in general cognitive control during language processing, including attention, working memory, and task execution, the specific roles and extent to which and where they occur in language might be mainly linked to executive demands rather than to the linguistic content itself. Therefore, the specific roles that MD areas play in language tasks remain uncertain, as their involvement may be tied primarily to control demands rather than to any innate language processing. In other words, though regions within the occipital cortex were found to be activated during linguistic tasks, including syntactic processing, emphasizing the transition from visual to linguistic functions in the absence of vision, this result may, in fact, be due to the content of higher cognitive function rather than the transition from visual to linguistic functions in blind.

1.11 Current Study

All in all, depending on the complexity or difficulty of the task, MD regions can help with the adaptive distribution of cognitive processes, including language. However, another study suggests that the involvement of these areas may be more closely related to executive functions than to directly supporting linguistic processing [76]. Overall, since current evidence only suggests the involvement of MD areas without providing a clear understanding of their specific contributions, more work is needed to fully understand the different and overlapping roles of MD areas in language processing and cognitive control.

Specifically, my current research examines whether V1 activation in blind individuals occurs selectively in tasks requiring cognitive control, such as attention and decision-making, or whether it also applies to tasks with minimal cognitive demand, such as passive listening. As previously indicated, our previous finding [2] demonstrated that V1 and MD network are functionally connected; this research is supported by activation in response to strong cognitive-control demands

on almost the entire occipital cortex in addition to the fronto-parietal MD regions.

Therefore, this thesis extends the notion by investigating the impact of cognitive-control demand in V1 activation during language tasks with minimal cognitive control requirements. By that, it aims to understand if this activation pattern is specific to cognitively demanding tasks or if it also appears when there is a minimal cognitive control demand.

This research points out a key gap in the field by examining if V1 activation in the blind depends on the degree of cognitive control demand. Although previous findings indicated V1 involvement in language tasks with high cognitive load, studies have yet to be conducted on whether minimal control-demand tasks (e.g., passive listening tasks) also activate V1. This study will clarify the conditions under which the visual cortex of blind people integrates the MD network by comparing V1 responses when general demands associated with performing a language task are kept to a minimum. This will provide insight into the specificity of V1's role in adaptive cognitive functions that go beyond sensory processing.

Our hypothesis for this study is that if V1 activation in the blinds really becomes a cognitive control demand, there should be no V1 activation due to minimal cognitive control in this passive listening task. This is because linguistic computations in language tasks in the literature, such as blocking irrelevant meanings, keeping representations active in working memory, or predicting upcoming elements, have this activation because they involve high cognitive control demand due to domain-general executive resources [64]. Therefore, in a task with minimal cognitive control demand, these factors will be eliminated, and an independent language task should not activate V1.

Chapter 2

Methods

2.1 Participants

The study comprised a total of 34 participants. Of these, 15 were sighted (M = 22.8), and 19 were blind M = 29.8). Of blind participants, 11 were congenitally blind, and 8 of them had acquired blindness later, before 18 years old. There were 2 left-handed and 17 right-handed participants in blind participants, while 13 of the participants were right-handed dominant and 2 were left-handed dominant among the sighted participants. In the sighted group, participants' eyes were covered with an eyepatch, and it was ensured that they did not see anything during the experiment. While blind participants reported no sight, rather than just a weak light perception, as stated in their medical reports. None of the participants had any neurological disease.

All participants were Turkish, so the task was conducted in Turkish. Ethics approval was taken from Bilkent University Ethics Committee For Research With Human Participants, and all participants' informed consent was taken before the session. Blind participants were paid 700 TL as a participation fee.

2.2 MRI Acquisition

For all participants, MRI scans were conducted using the 12-channel phased head coil. Data were acquired using T2*-weighted echo planar imaging (EPI) with a single-shot gradient echo. The acquisition parameters were: 32 oblique slices (slice thickness = 3 mm; interslice gap = 0.75 mm), repetition time (TR) = 2000 ms, echo time (TE) = 30 ms, matrix size = 64 × 64, in-plane resolution = 3.0 × 3.0 mm, and field of view (FoV) = 192 mm. High-resolution anatomical images were collected before the functional scans using a T1-weighted magnetization-prepared rapid acquisition gradient echo (MPRAGE) sequence with 176 sagittal slices, a slice thickness of 1 mm, isotropic voxel resolution of 1 mm^3, and a FoV of 256 mm.

2.3 Data Collection

Participants first underwent a T1-weighted image scan before proceeding to the functional task. During the functional task, they listened to the auditory stimuli through MRI-compatible headphones. The functional scan lasted approximately 20 minutes, during which participants followed the instructions provided and used a button box held to respond as required (see Figure 2.1).

2.4 Task

2.4.1 Passive Listening with Minimal Cognitive Control Demand

This passive listening task was designed so that participants did not actively use the language but only tried to understand what was said, leading to minimal cognitive control demands. The task contained passages from the story of Alice

in Wonderland, and the stimuli for these story passages were taken from [79]. These passages consisted of random excerpts, each lasting 18 seconds. The task began with a 15-second rest period. It included two conditions, with each block initiated by a button press from the participant following an instruction. Pre-recorded task instructions and stimuli were delivered through headphones while participants were in the scanner. After pressing the button, the first block began, corresponding to the language condition. In this block, participants listened to an 18-second recording of a storyteller's clear voice. This was followed by a jittered rest period lasting between 5 and 15 seconds. Once the rest period ended, participants were instructed to press a button again to start the next block, which was the non-language condition. In this condition, low-pass filtering was applied to soften high frequencies, rendering the passages unintelligible. At the end of this block, the same steps are repeated. All passages were randomized, there was no requirement for them to be the same as the previous passage. The experiment concluded after participants completed 40 blocks, consisting of 20 blocks for each condition (language and non-language) presented in a fixed order. The task ended with a final 15-second rest period.

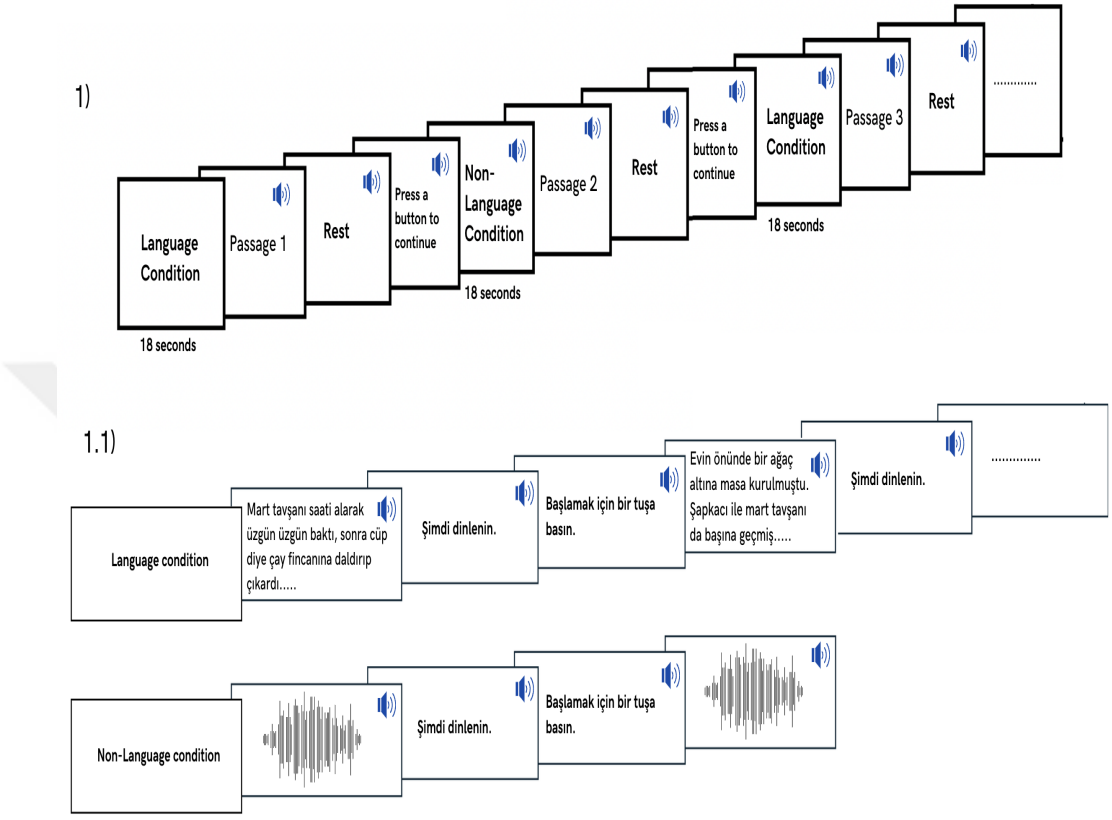

Figure 2.1: Overview of functional MRI passive listening task with minimal control demand.

2.5 Analyses of Data

All analysis steps were done in two ways: whole brain and standard space ROI (Region of Interest). Therefore, the analyses will be examined in two separate ways.

2.5.1 Pre-processing of the Data

For analyses in normalized space, preprocessing was performed using the 5th version of automatic analysis (aa) and DARTEL (Diffeomorphic Anatomical Registration Through Exponentiated Lie Algebra), [80]. This algorithm was chosen for its superior spatial accuracy, as it uses a flexible, non-linear approach to capture finer anatomical details, making it more precise compared to other normalization methods. Second, unlike other approaches that normalize each brain to a single fixed template, it creates a study-specific template based on the participants' average structure. Additionally, the two-step normalization process in DARTEL helps minimize individual anatomical differences, which in turn helps us obtain more concrete results in group analyses. This is particularly useful for understanding subtle anatomical differences between groups or, as in this study, for understanding functional activity in specific areas. As a final note, analyses were performed using SPM12 (2014), developed by the Wellcome Trust Centre for Neuroimaging in MATLAB.

2.5.2 fMRI Analysis and Modelling

This statistical analysis was conducted with a general linear model (GLM). A 128-second high-pass cutoff filter was applied to each voxel. In total, four regressors were applied: language, non-language, press, and rest. Each of these regressors was modeled over the entire corresponding period. Six movement parameters have been integrated into GLM, along with no-interest regressors. Each of these regressors was convolved with a conventional hemodynamic response function. The four regressors' contrasts mentioned in the task were created with the vectors $Language > Non - Language$, Task $(Language + Non - Language) > Rest$, $Language > Rest$, $Non - Language > Rest$. Group-level analyses are conducted for the blind and sighted; comparative analysis of them ($blind > sighted$) on $Language > Non - Language$ contrast.

2.5.3 ROI Analyses

Region of Interest (ROI) analysis was conducted in different brain regions in both blind and control participants. In order to make comparisons between participants over different brain regions, Language and Non-Language mean differences were examined. In the examined brain regions, V1 and ESV regions within the occipital cortex were analyzed to determine whether their values significantly deviated from zero, as visual inspection did not provide conclusive results. Additionally, fronto-parietal and temporal regions were also included in the analysis; these masks were created from Jubrain Anatomy Toolbox [51], [60], JuBrain Toolbox [81]. These ROI-based statistical analyses were performed using JASP [82].

Chapter 3

Results

As discussed in the introduction, we wanted to investigate if the primary visual cortex of the blind would still activate language processing when domain-general demands related to task execution are minimized. Hence, we used a passive listening task and compared activity when participants were passively listening to a text being read to periods when they were listening to incomprehensible noise that was matched to the text reading in lower-level sensory characteristics.

Crucially, visual regions did not significantly activate, showing no trend toward significant activation. The Bayesian Repeated Measures ANOVA demonstrated that none of the ROIs deviated significantly from zero activity under the experimental conditions.

As evident in Figure 3.1, only the canonical language regions activated to language processing demands evoked by listening to the text being read. These included the inferior frontal gyrus (IFG), known as Broca's Area, and the superior temporal gyrus (STG), known as Wernicke's Area.

Importantly, blind and sighted participants largely activated the same regions during language processing. A direct contrast between them showed no difference in visual cortical activation to language processing. This was also confirmed by an ROI analysis of language regions (Figure 6). Similarly, MD regions across

participants activated almost the same regions. A direct contrast between them showed no difference between groups. An ROI analysis of MD regions confirmed this as well.

Curiously, we found that blind and sighted differed in primary somatosensory (S1) and primary motor (M1) areas.

3.1 Whole Brain Analyses

For the whole brain analyses, statistical maps were thresholded using a false discovery rate (FDR) correction at $p < .05$, corresponding to a t-value of 4.0. This threshold was set by controlling the expected false positive rate among voxels that was declared significant, ensuring that reported activations represented robust and reliable findings [83]; [84].

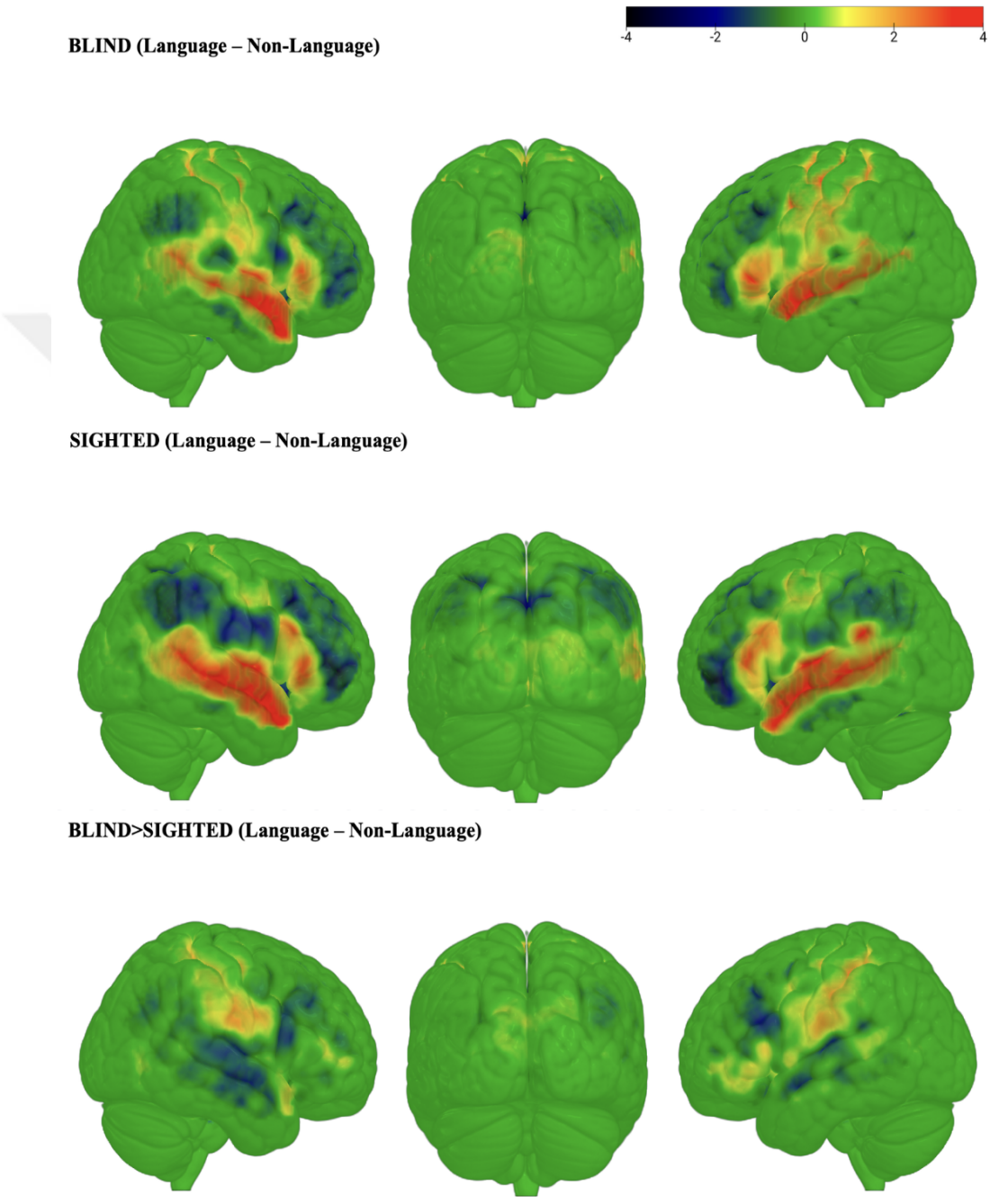

Figure 3.1: Whole-brain analyses on the passive listening task. (a) activation and deactivation in blind participants, (b) activation and deactivation in sighted participants, (c) *blind* > *language* comparative brain activation and deactivation results are shown on language-non-language contrast (Language: +1; Non-Language -1).

Importantly, the results showed no significant visual cortex activation in contrast to language – non-language across all groups.This supports our hypothesis that this region is not recruited for language, specifically in the blind. This strengthens the task dependence of V1 responses and suggests that plasticity in the visual cortex depends on specific task demands, such as higher cognitive control demands, but we will revisit this in a detailed analysis based on the region.

In the blind group, the superior temporal gyrus (STG), part of the middle temporal gyrus (MTG), and the precentral gyrus (M1) showed activation. Additionally, the Default Mode Network (DMN), including the inferior parietal lobe and the right angular gyrus, part of the inferior parietal lobule (IPL), exhibited deactivation. Notably, these patterns were observed bilaterally. Similar patterns are observed in the sighted group in visual observation, but the superior and middle temporal gyri appear more prominent. Increased deactivation in the posterior parietal cortex (PPC) and adjacent areas might suggest reduced demands. Suppression of default mode regions (e.g., angular gyrus) appears greater in visual inspection compared to the previous blind group.

This deactivation of the Default Mode Network (DMN), including the inferior parietal lobule (IPL) and angular gyrus, likely reflects the brain's efficient distribution of resources to auditory and linguistic processing, which are critical for task performance in both blind and sighted groups. This reallocation of DMN leads to deactivation in these regions, highlighting their non-involvement with unrelated cognitive activities during the task instead of prioritizing.

In the comparison between groups, activation of the angular gyrus, bilateral precentral gyrus (M1), and bilateral postcentral gyrus (S1) was observed.

Compared to the blind group, the superior and middle temporal gyri exhibit more notable activation, which may reflect a stronger reliance on auditory and linguistic processing in the sighted group, potentially due to the absence of reorganization of the brain related to sensory loss.

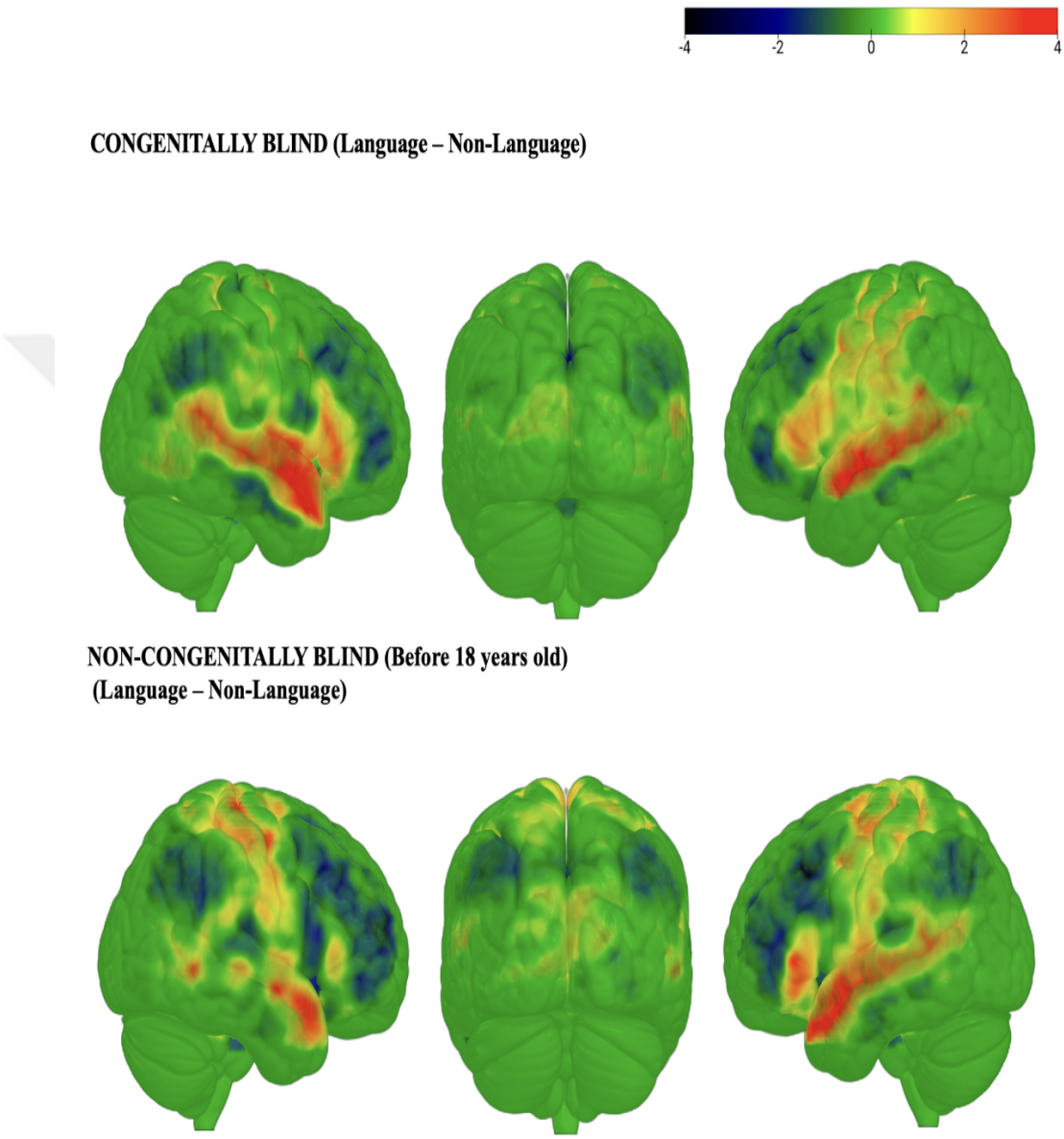

Figure 3.2: Whole-brain analyses in different blind groups on the passive listening task. (a) activation and deactivation in congenitally blind participants (b) activation and deactivation in non-congenitally blind participants' results are shown on language-non-word contrast (Language: +1; Non-Language -1).

Separate group-level analysis of congenital and non-congenitally blind participants revealed that non-congenitally blind participants showed greater deactivation in the medial prefrontal cortex (mPFC) and prefrontal cortex (PFC) compared to the congenital group. Similarly, stronger deactivation was observed in the posterior parietal cortex, particularly near the intraparietal sulcus (IPS) and superior parietal lobule (SPL), in non-congenitally blind participants than in congenital. As the visual inspection shows, mild V1 activation in non-congenitally blind individuals may indicate a task-dependent and residual response in V1; however, note that this effect is non-significant. The small activation here may be due to the non-congenitally blind participants losing their vision in later life and thus retaining some functional aspects of V1 visual processing. This residual capacity may allow limited engagement during low-demand tasks, but it should be noted that activation is not robust.

The stronger deactivation in the IPS and SPL in the non-congenitally blind could be related to task-specific mechanisms, such as reduced demands in control mechanisms as we expect in such task. In contrast, less deactivation showed in the congenitally blind in these regions could be because of their reliance on other sensory integration tasks that are distributed across these parietal areas.

The greater prefrontal deactivation in the congenitally blind could indicate that their executive control mechanisms are redistributed to other networks, especially in this minimal cognitive control demand task. Non-congenitally blind individuals may rely more on visual strategies or engage areas tied to prior visual experience, limiting the extent of reorganization in frontal areas since the story may lead to visual imagination because of its nature.

3.2 ROI Analyses

3.2.1 ROI Analysis on Occipital Regions

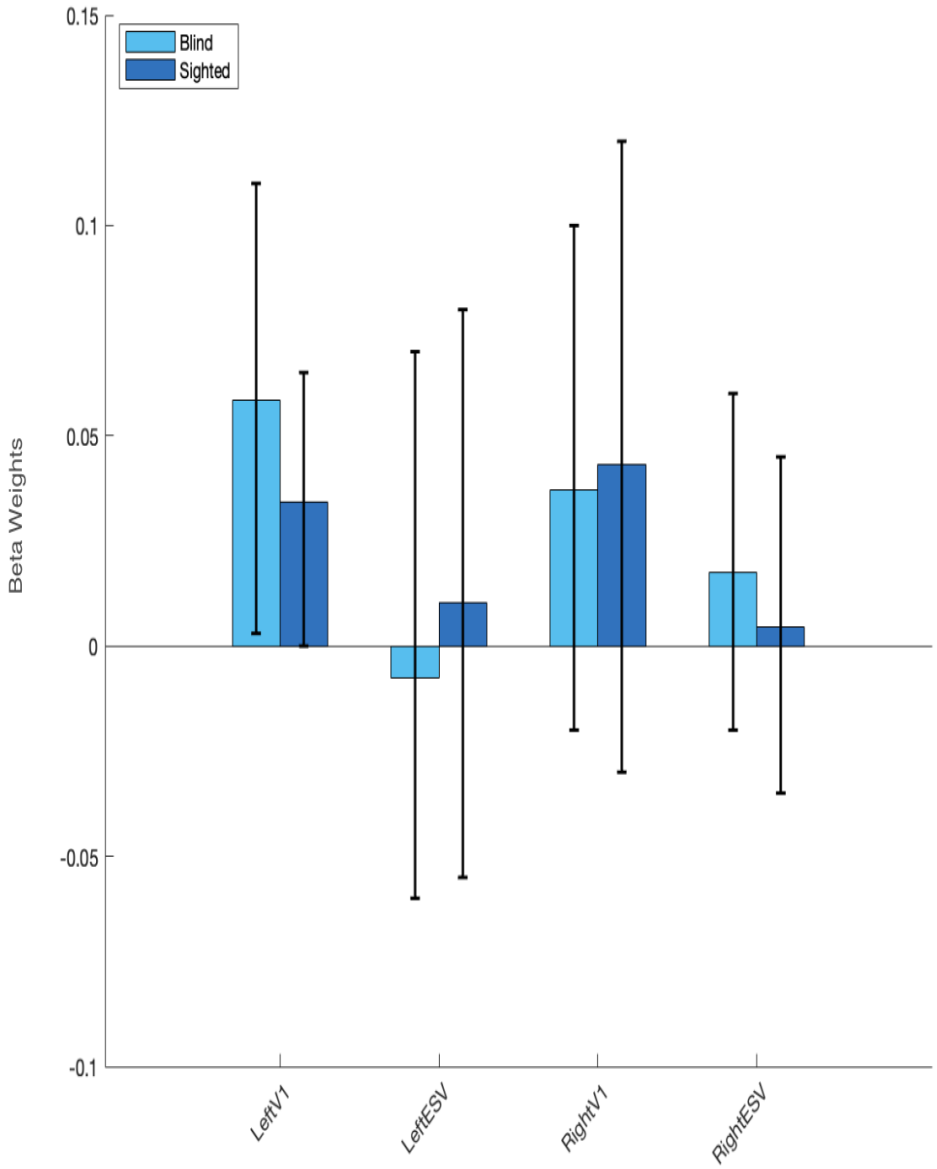

Figure 3.3: Bayesian Repeated Measures ANOVA analysis on deviation from zero on mean differences of Language and Non-Language conditions both in blind and sighted groups on V1 and ESV regions. Error bars indicate 95% CI

A Bayesian Repeated Measures ANOVA was conducted to test whether the activity levels in these regions significantly deviated from zero (i.e., whether each ROI activity was positive or negative). The model comparison revealed moderate evidence for the null hypothesis (BF_{01}= 3.25). Furthermore, regarding the main effect of ROI activity, again it showed moderate evidence (BF_{01}= 5.94). This indicates that none of the ROIs exhibited significant deviations from zero activity under the experimental conditions. This result supports the interpretation that the task of passive listening did not cause significant activation in the V1 or ESV in the occipital cortex.

Importantly, the lack of significant activity in V1 and ESV supports the interpretation that the passive listening task, which imposed minimal cognitive control demands, did not require the recruitment of visual cortices, even in blind participants.

3.2.2 ROI Analysis on Language Regions

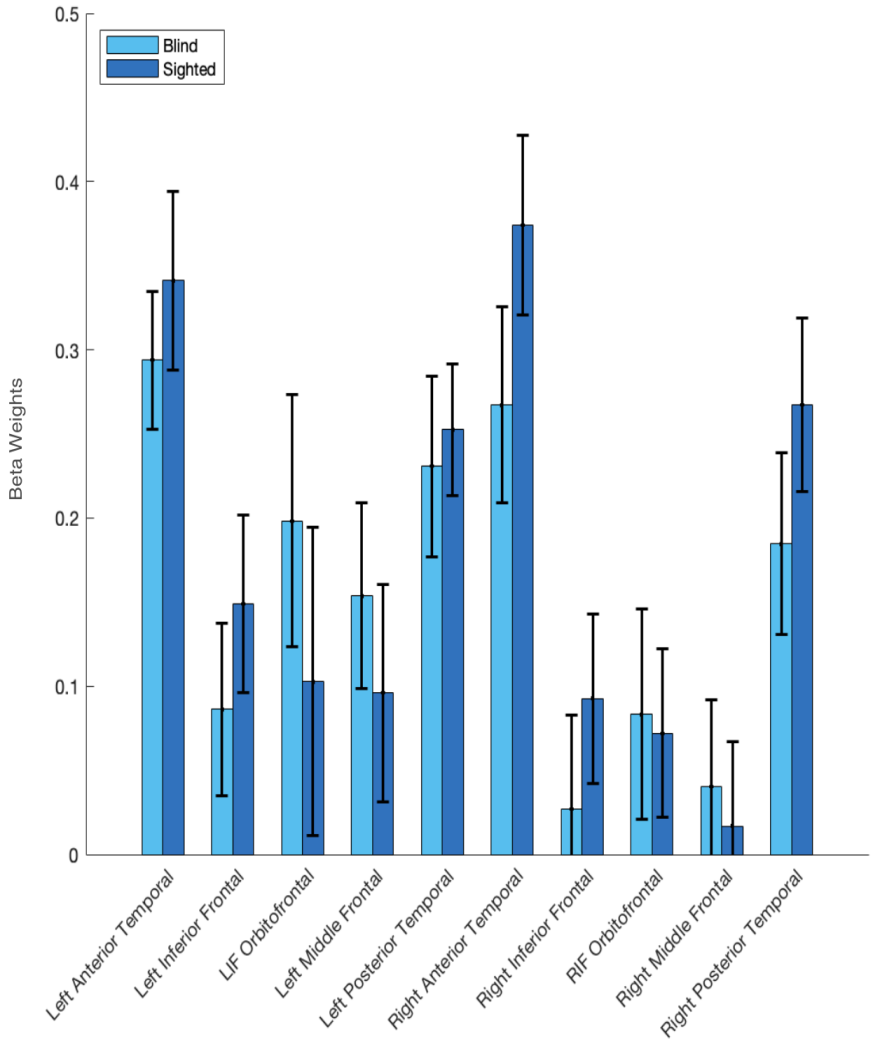

Figure 3.4: Repeated Measures ANOVA analysis on mean differences of Language and Non-Language conditions both in blind and sighted groups on language regions. Error bars indicate 95% CI

When the language regions of blind and control participants were compared in the focus of a passive listening task, Repeated Measures ANOVA results showed that the between-subjects effect of Group (Blind vs. Sighted) was not significant ($F(1,32) = 0.106$, $p = 0.747$, $\eta_p^2 = 0.003$), indicating no overall difference in activity between groups. The interaction effect between Group and ROI was also not

significant ($F(5.171,165.472) = 1.334$, $p = 0.251$, $\eta_p^2 = 0.04$, $\epsilon = 0.573$), suggesting group differences in activity did not vary significantly across ROIs. Overall, no significant differences were found between the language regions of the participants. However, a significant main effect of ROI was observed ($F(5.17,165.47) = 13.68$, $p < .001$, $\eta_p^2 = 0.30$, $\epsilon = 0.573$), indicating that activity levels differed across ROIs, irrespective of group differences. This finding highlights distinct variations in activation patterns across specific language-related regions, independent from blind and sighted groups.

The lack of any differences between the groups in language regions might suggest that these networks function similarly for both blind and sighted individuals in a task that involves minimal cognitive control. The low cognitive demands of the task may have failed to elicit distinct activation patterns, as both groups rely on specialized, shared core neural circuits for language comprehension.

Upon detailed examination, the results show that the regions in the left hemisphere are more active, consistent with this region being more dominant in terms of language. This hemispheric specialization underlines the universal role of the left hemisphere in language tasks, reinforcing the idea that its function is preserved across diverse populations. This adds to the understanding of the stability and resilience of the neural mechanisms related to language, even against sensory loss.

3.2.3 ROI Analysis on MD Regions

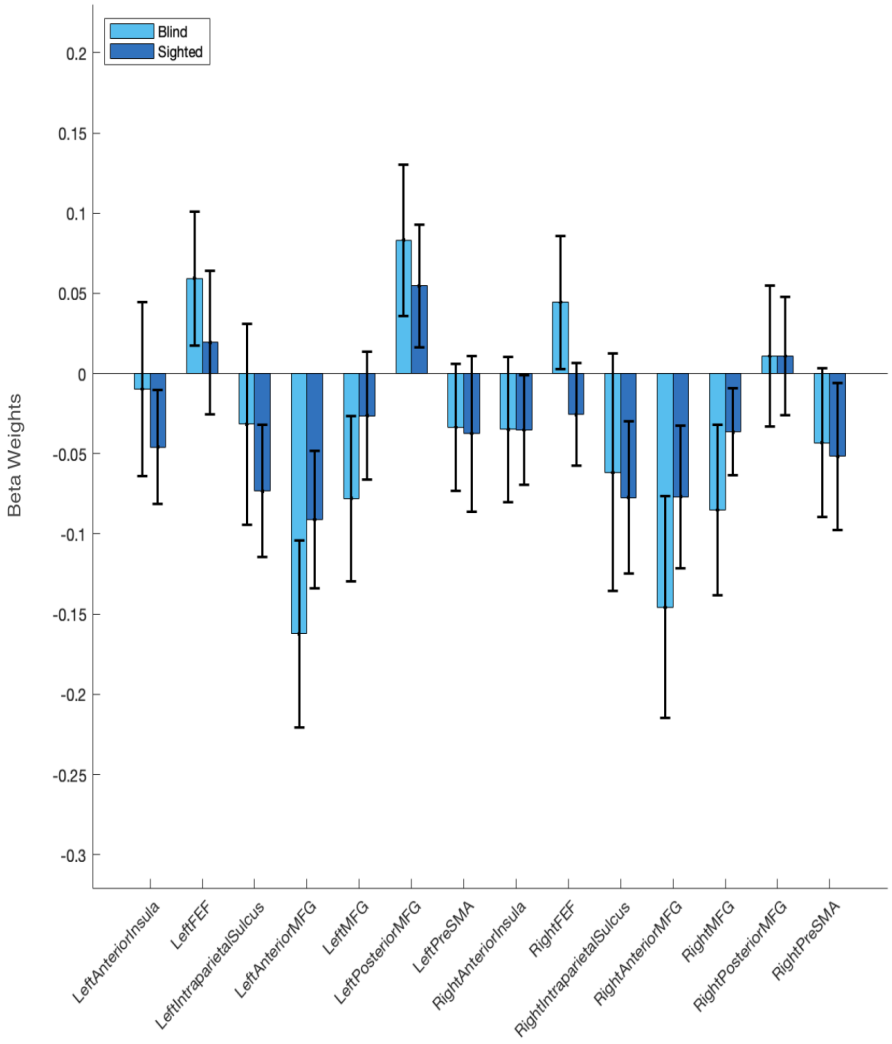

Figure 3.5: Repeated Measures ANOVA analysis on mean differences of Language and Non-Language conditions both in blind and sighted groups on MD regions. Error bars indicate 95% CI

A repeated measures ANOVA was conducted to investigate the interaction between ROI and Group in MD regions. The interaction effect between ROI and Group was not statistically significant ($F(4.85,155.09) = 1.18$, $p = .322$, η_p^2=.01). Similarly, the between-subjects effect of the Group was not statistically significant ($F(1,32) = 0.00003$, $p = .996$, $\eta_p^2 = 0.000$), indicating no overall group differences.

However, a repeated measures ANOVA revealed a significant main effect of ROI, indicating that activity levels varied across different ROIs, $F(4.85,155.09) = 6.89$, $p < .001$, $\eta_p^2 = 0.18$, ϵ=0.373.

Since MD regions inherently play an active role in higher cognitive control tasks, the lack of group differences in this study aligns with expectations, as the task was designed to impose minimal cognitive control demands. This finding further supports the notion that the task itself required only minimal engagement of cognitive control mechanisms. Furthermore, in connection with language regions, the deactivation observed in left MD regions during sentence processing may indicate that these areas are not required for active cognitive control (e.g., working memory, task switching) in this passive listening task. Instead, it relies on the default language pathways in traditional language areas and may be interpreted as deactivating MD regions, as these regions activate language areas such as Broca/Wernicke, reducing the need for MD regions. This deactivation pattern in MD regions might also indicate a closer functional relationship between left hemisphere MD regions and linguistic networks, as observed in these results.

Overall, MD regions mostly showed consistent activation and deactivation that matched the nature of the task and the region's function (e.g., preSMA being deactivated in the passive listening task).

Chapter 4

Discussion

The results showed that the minimal cognitive control task did not activate the primary visual cortex region. This lack of activation was due to a high cognitive control demand, unlike the language task, even though this challenges previous assumptions that V1 is universally reused for non-visual processing in the blind [32], [13], it is also important to note that V1 may be part of the language network in blind individuals and could contribute to processes such as syntax, semantics, or phonological decoding [24], [78]. However, this study did not find evidence that V1 is integrated into the language network despite engaging with core language areas involving phonological, lexical, syntactic, and semantic processes. It was understood that this task activated the specific processes mentioned above, especially the middle and inferior temporal gyri and the left inferior frontal gyrus, known as Broca's area, along with portions of the superior temporal sulcus that were activated after the whole brain analysis of the participants. It should be noted that this is a powerful language task, as the findings supported in the language regions, but importantly, the demand for cognitive control is minimal.

Another point that should be emphasized in this context is the comparison of congenitally blind participants with late blind participants in V1. Although the activation results proved not significantly different from zero, a few things can be mentioned about this visual inspection. Based on evidence from the

literature, it is known that the timing of the deprivation matters in the case of functional organization of the brain and connectivity [85]. This provides an important perspective: If the V1 region of the blind were to be transformed to language processing tasks, this effect would require greater activation in the congenitally blind when comparing congenitally and late blind. However, the effect, although not robust, was found in people who were late blind. The reason for this effect in the non-congenitally blind may be that even though the sensory loss is complete, the area was previously visually active, and different remnants are present. The conclusion is that the demand for cognitive control evidences this activation pattern.

As evidence that this cognitive control demand is minimal, ROI analyses performed specifically for MD regions can be examined in detail. The domain-general cognitive processes included in this region are involved in processes such as working memory, task-switching, and attention [56], and some important brain regions regarding those can be described as Inferior Parietal Sulcus (IPS), Supplementary Motor Area (SMA), and Anterior Cingulate Cortex (ACC) [56]. Remember that these regions are flexible centers that control neural activity related to cognitive load rather than being related to specific sensory modalities [1]. This difference, which comes into play at this point and is not found specifically for MD regions, is due to minimal cognitive control demand. Because, in this task, participants are not actively involved in situations such as decision-making, hierarchical order, or task-switching. Therefore, there is no between-subject difference, possibly due to MD regions' similar minimal degree of involvement. To summarize this relationship between MD regions, their activation and deactivation patterns are pretty much consistent with the literature, and the non-significant difference is expected for those reasons above.

Another point that needs to be mentioned is the language regions. Similarly, no differences were observed among the participants in the language regions. These language regions are responsible for the processing of syntax and semantic processes as well as phonology, which are crucial for understanding the language and its structure [72], [70]. The results of this task and the ROI analysis in the language regions demonstrated that the task successfully activated language regions,

particularly Broca's and Wernicke's areas. These findings align with existing literature, highlighting the relationship between the task content and language regions without introducing additional cognitive control demands. Language regions, like MD regions, have more core and resistive functions [72], suggesting that this can be preserved even in deprived sensory cortex conditions. This illustrates how language areas resistant to sensory deprivation are domain-specific [74]. Similarly, language regions are more active in the left hemisphere may be attributed to the left hemisphere's dominance in language processing [86]. This further supports the notion that language regions retain their specificity. In other words, rather than adopting a different region such as V1, the core language networks remain functionally intact and sufficient for processing linguistic stimuli.

Interestingly, the difference in M1 and S1 regions between blind and sighted participants, which is seen outside the scope of the hypothesis, remains an open question. Although it is well-established that these cortices show high task dependence [87], it is still unclear how this feature might lead to neuroplastic adaptations in the blind. While such cortices have been shown to undergo reorganization in cases like amputation [88], the degree and functional relevance of such changes in the blind are still unknown. Further research is strongly needed to provide well-founded interpretations.

Lastly, it is important to address the differences in the age of blindness onset among the non-congenitally blind participants. While all individuals in this group became blind before the age of 18, the onset of blindness occurred at varying ages, ranging from as early as 3 years to later ages such as 6 or 9 years. This variability allows for further investigation of how the timing of blindness acquisition, particularly at early and late developmental stages, may influence neuroplastic adaptations and cognitive functioning.

In conclusion, both MD and language regions are selectively recruited across task demands, comparing high and low demands. The minimal demands of the passive listening task resulted in similar activation patterns across groups for both networks. Neither MD nor language regions showed significant cross-modal recruitment (e.g., from V1) during the passive task, highlighting the variations

of neuroplasticity in sensory-deprived populations. This finding highlights the role of task complexity in the regulation of neural activation and highlights the specificity of cross-modal in blind individuals. It also highlights the understanding of how sensory loss affects the functional organization of the brain.

By integrating these results with previous research, this study contributes to a detailed understanding of how sensory loss shapes the functional organization of the brain. Thus, more robust evidence is provided for the role of V1, supporting the idea that in blind individuals, the visual cortex can be repurposed for tasks requiring cognitive control, suggesting that it plays domain-general roles beyond sensory or language-specific functions.

4.1 Conclusion

In light of all of these above, the absence of V1 activation during passive listening tasks in blind subjects highlights a critical specificity of V1 in its adaptive function. This study clarifies the conditions under which V1 responses in cognitively demanding language tasks are integrated into the MD network of the visual cortex, not necessarily the language tasks themselves. Therefore, it provides new insights into the selective role of V1 in adaptive cognitive functions and suggests that integration of V1 into the MD network may be uniquely linked to tasks requiring active cognitive control. This specificity aims to make an important contribution to the existing literature by reshaping our understanding of how the deprived sensory cortices in blind do not become a part of language regions.

Bibliography

[1] E. Fedorenko, J. Duncan, and N. Kanwisher, "Broad domain generality in focal regions of frontal and parietal cortex," *Proceedings of the National Academy of Sciences*, vol. 110, no. 41, pp. 16616–16621, 2013.

[2] H. Duymuş, M. Verma, Y. Güçlütürk, M. Öztürk, A. B. Varol, Ş. Kurt, T. Gezici, B. F. Akgür, İ. Giray, E. E. Öksüz, *et al.*, "The visual cortex in the blind but not the auditory cortex in the deaf becomes multiple-demand regions," *Brain*, p. awae187, 2024.

[3] A. Pascual-Leone, A. Amedi, F. Fregni, and L. B. Merabet, "The plastic human brain cortex," *Annu. Rev. Neurosci.*, vol. 28, no. 1, pp. 377–401, 2005.

[4] T. R. Makin and J. W. Krakauer, "Against cortical reorganisation," *elife*, vol. 12, p. e84716, 2023.

[5] M. M. Merzenich, R. J. Nelson, M. P. Stryker, M. S. Cynader, A. Schoppmann, and J. M. Zook, "Somatosensory cortical map changes following digit amputation in adult monkeys," *Journal of comparative Neurology*, vol. 224, no. 4, pp. 591–605, 1984.

[6] B. Kolb and I. Q. Whishaw, "Brain plasticity and behavior," *Annual review of psychology*, vol. 49, no. 1, pp. 43–64, 1998.

[7] J. Villablanca and D. Hovda, "Developmental neuroplasticity in a model of cerebral hemispherectomy and stroke," *Neuroscience*, vol. 95, no. 3, pp. 625–637, 1999.

[8] A. E. Telfeian, C. Berqvist, C. Danielak, S. L. Simon, and A.-C. Duhaime, "Recovery of language after left hemispherectomy in a sixteen-year-old girl with late-onset seizures," *Pediatric neurosurgery*, vol. 37, no. 1, pp. 19–21, 2002.

[9] P. Wangaryattawanich, A. M. Rutman, S. Petcharunpaisan, and M. Mossa-Basha, "Incidental findings on brain magnetic resonance imaging (mri) in adults: a review of imaging spectrum, clinical significance, and management," *The British Journal of Radiology*, vol. 96, no. 1142, p. 20220108, 2023.

[10] S. Nakasu, A. Hirano, T. Shimura, and J. F. Llena, "Incidental meningiomas in autopsy study," *Surgical neurology*, vol. 27, no. 4, pp. 319–322, 1987.

[11] D. Kliemann, R. Adolphs, J. M. Tyszka, B. Fischl, B. T. Yeo, R. Nair, J. Dubois, and L. K. Paul, "Intrinsic functional connectivity of the brain in adults with a single cerebral hemisphere," *Cell reports*, vol. 29, no. 8, pp. 2398–2407, 2019.

[12] B. Kolb and R. Gibb, "Brain plasticity and behaviour in the developing brain," *Journal of the Canadian Academy of Child and Adolescent Psychiatry*, vol. 20, no. 4, p. 265, 2011.

[13] N. Sadato, A. Pascual-Leone, J. Grafman, V. Ibañez, M.-P. Deiber, G. Dold, and M. Hallett, "Activation of the primary visual cortex by braille reading in blind subjects," *Nature*, vol. 380, no. 6574, pp. 526–528, 1996.

[14] L. G. Cohen, P. Celnik, A. Pascual-Leone, B. Corwell, L. Faiz, J. Dambrosia, M. Honda, N. Sadato, C. Gerloff, M. D. Catalá, *et al.*, "Functional relevance of cross-modal plasticity in blind humans," *Nature*, vol. 389, no. 6647, pp. 180–183, 1997.

[15] C. Büchel, C. Price, R. Frackowiak, and K. Friston, "Different activation patterns in the visual cortex of late and congenitally blind subjects.," *Brain: a journal of neurology*, vol. 121, no. 3, pp. 409–419, 1998.

[16] L. B. Merabet and A. Pascual-Leone, "Neural reorganization following sensory loss: the opportunity of change," *Nature Reviews Neuroscience*, vol. 11, no. 1, pp. 44–52, 2010.

[17] D. H. Hubel and T. N. Wiesel, "Early exploration of the visual cortex," *Neuron*, vol. 20, no. 3, pp. 401–412, 1998.

[18] V. B. Mountcastle, "The columnar organization of the neocortex.," *Brain: a journal of neurology*, vol. 120, no. 4, pp. 701–722, 1997.

[19] M. Mesulam, "From sensation to perception," *Brain*, vol. 121, pp. 1013–1052, 1998.

[20] B. A. Wandell and S. M. Smirnakis, "Plasticity and stability of visual field maps in adult primary visual cortex," *Nature Reviews Neuroscience*, vol. 10, no. 12, pp. 873–884, 2009.

[21] D. H. Hubel and T. N. Wiesel, "Brain mechanisms of vision," *Scientific American*, vol. 241, no. 3, pp. 150–163, 1979.

[22] D. H. Hubel and T. N. Wiesel, "The period of susceptibility to the physiological effects of unilateral eye closure in kittens," *The Journal of physiology*, vol. 206, no. 2, pp. 419–436, 1970.

[23] H. Bridge, A. Cowey, N. Ragge, and K. Watkins, "Imaging studies in congenital anophthalmia reveal preservation of brain architecture in 'visual'cortex," *Brain*, vol. 132, no. 12, pp. 3467–3480, 2009.

[24] M. Bedny, A. Pascual-Leone, D. Dodell-Feder, E. Fedorenko, and R. Saxe, "Language processing in the occipital cortex of congenitally blind adults," *Proceedings of the National Academy of Sciences*, vol. 108, no. 11, pp. 4429–4434, 2011.

[25] A. Amedi, N. Raz, P. Pianka, R. Malach, and E. Zohary, "Early 'visual'cortex activation correlates with superior verbal memory performance in the blind," *Nature neuroscience*, vol. 6, no. 7, pp. 758–766, 2003.

[26] H. Flor, M. Diers, and J. Andoh, "The neural basis of phantom limb pain," *Trends in cognitive sciences*, vol. 17, no. 7, pp. 307–308, 2013.

[27] L. A. Henderson, S. M. Gustin, P. M. Macey, P. J. Wrigley, and P. J. Siddall, "Functional reorganization of the brain in humans following spinal cord injury: evidence for underlying changes in cortical anatomy," *Journal of Neuroscience*, vol. 31, no. 7, pp. 2630–2637, 2011.

[28] C. Y. Wan and G. Schlaug, "Music making as a tool for promoting brain plasticity across the life span," *The Neuroscientist*, vol. 16, no. 5, pp. 566–577, 2010.

[29] M. S. Thomas and M. H. Johnson, "New advances in understanding sensitive periods in brain development," *Current directions in psychological science*, vol. 17, no. 1, pp. 1–5, 2008.

[30] R. Kupers and M. Ptito, "Compensatory plasticity and cross-modal reorganization following early visual deprivation," *Neuroscience & Biobehavioral Reviews*, vol. 41, pp. 36–52, 2014.

[31] M.-C. Wanet-Defalque, C. Veraart, A. De Volder, R. Metz, C. Michel, G. Dooms, and A. Goffinet, "High metabolic activity in the visual cortex of early blind human subjects," *Brain research*, vol. 446, no. 2, pp. 369–373, 1988.

[32] R. Kupers, M. Beaulieu-Lefebvre, F. Schneider, T. Kassuba, O. Paulson, H. Siebner, and M. Ptito, "Neural correlates of olfactory processing in congenital blindness," *Neuropsychologia*, vol. 49, no. 7, pp. 2037–2044, 2011.

[33] L. Renier, I. Cuevas, C. B. Grandin, L. Dricot, P. Plaza, E. Lerens, P. Rombaux, and A. G. De Volder, "Right occipital cortex activation correlates with superior odor processing performance in the early blind," *PLoS One*, vol. 8, no. 8, p. e71907, 2013.

[34] S. Abboud, S. Hanassy, S. Levy-Tzedek, S. Maidenbaum, and A. Amedi, "Eyemusic: Introducing a "visual" colorful experience for the blind using auditory sensory substitution," *Restorative neurology and neuroscience*, vol. 32, no. 2, pp. 247–257, 2014.

[35] H. Burton, A. Z. Snyder, T. E. Conturo, E. Akbudak, J. M. Ollinger, and M. E. Raichle, "Adaptive changes in early and late blind: a fmri study of braille reading," *Journal of neurophysiology*, vol. 87, no. 1, pp. 589–607, 2002.

[36] M. Bedny, H. Richardson, and R. Saxe, ""visual" cortex responds to spoken language in blind children," *Journal of Neuroscience*, vol. 35, no. 33, pp. 11674–11681, 2015.

[37] S. Kanjlia, C. Lane, L. Feigenson, and M. Bedny, "Absence of visual experience modifies the neural basis of numerical thinking," *Proceedings of the National Academy of Sciences*, vol. 113, no. 40, pp. 11172–11177, 2016.

[38] E. Ricciardi and P. Pietrini, "New light from the dark: what blindness can teach us about brain function," *Current opinion in neurology*, vol. 24, no. 4, pp. 357–363, 2011.

[39] J. Driver and T. Noesselt, "Multisensory interplay reveals crossmodal influences on 'sensory-specific'brain regions, neural responses, and judgments," *Neuron*, vol. 57, no. 1, pp. 11–23, 2008.

[40] D. Bavelier and H. J. Neville, "Cross-modal plasticity: where and how?," *Nature Reviews Neuroscience*, vol. 3, no. 6, pp. 443–452, 2002.

[41] B. Röder, O. Stock, S. Bien, H. Neville, and F. Rösler, "Speech processing activates visual cortex in congenitally blind humans," *European Journal of Neuroscience*, vol. 16, no. 5, pp. 930–936, 2002.

[42] O. Collignon, P. Voss, M. Lassonde, and F. Lepore, "Cross-modal plasticity for the spatial processing of sounds in visually deprived subjects," *Experimental brain research*, vol. 192, pp. 343–358, 2009.

[43] H.-K. Lee, "Metaplasticity framework for cross-modal synaptic plasticity in adults," *Frontiers in Synaptic Neuroscience*, vol. 14, p. 1087042, 2023.

[44] J. C. Culham and K. F. Valyear, "Human parietal cortex in action," *Current opinion in neurobiology*, vol. 16, no. 2, pp. 205–212, 2006.

[45] A. Pascual-Leone and R. Hamilton, "The metamodal organization of the brain," *Progress in brain research*, vol. 134, pp. 427–445, 2001.

[46] G. Dormal, M. Rezk, E. Yakobov, F. Lepore, and O. Collignon, "Auditory motion in the sighted and blind: early visual deprivation triggers a large-scale imbalance between auditory and "visual" brain regions," *Neuroimage*, vol. 134, pp. 630–644, 2016.

[47] M. Bedny, "Evidence from blindness for a cognitively pluripotent cortex," *Trends in cognitive sciences*, vol. 21, no. 9, pp. 637–648, 2017.

[48] O. Collignon, G. Vandewalle, P. Voss, G. Albouy, G. Charbonneau, M. Lassonde, and F. Lepore, "Functional specialization for auditory–spatial processing in the occipital cortex of congenitally blind humans," *Proceedings of the National Academy of Sciences*, vol. 108, no. 11, pp. 4435–4440, 2011.

[49] D. Norman, "Attention to action: Willed and automatic control of behavior," *Consciousness and self-regulation: Advances in research and theory*, vol. 4, 1986.

[50] A. Miyake, N. P. Friedman, M. J. Emerson, A. H. Witzki, A. Howerter, and T. D. Wager, "The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: A latent variable analysis," *Cognitive psychology*, vol. 41, no. 1, pp. 49–100, 2000.

[51] M. B. Jurado and M. Rosselli, "The elusive nature of executive functions: A review of our current understanding," *Neuropsychology review*, vol. 17, pp. 213–233, 2007.

[52] E. K. Miller and J. D. Cohen, "An integrative theory of prefrontal cortex function," *Annual review of neuroscience*, vol. 24, no. 1, pp. 167–202, 2001.

[53] M. M. Botvinick, T. S. Braver, D. M. Barch, C. S. Carter, and J. D. Cohen, "Conflict monitoring and cognitive control.," *Psychological review*, vol. 108, no. 3, p. 624, 2001.

[54] M. Corbetta and G. L. Shulman, "Control of goal-directed and stimulus-driven attention in the brain," *Nature reviews neuroscience*, vol. 3, no. 3, pp. 201–215, 2002.

[55] N. U. Dosenbach, D. A. Fair, A. L. Cohen, B. L. Schlaggar, and S. E. Petersen, "A dual-networks architecture of top-down control," *Trends in cognitive sciences*, vol. 12, no. 3, pp. 99–105, 2008.

[56] J. Duncan, "The multiple-demand (md) system of the primate brain: mental programs for intelligent behaviour," *Trends in cognitive sciences*, vol. 14, no. 4, pp. 172–179, 2010.

[57] J. Duncan and A. M. Owen, "Common regions of the human frontal lobe recruited by diverse cognitive demands," *Trends in neurosciences*, vol. 23, no. 10, pp. 475–483, 2000.

[58] J. Duncan, "An adaptive coding model of neural function in prefrontal cortex," *Nature reviews neuroscience*, vol. 2, no. 11, pp. 820–829, 2001.

[59] A. A. Farooqui, D. Mitchell, R. Thompson, and J. Duncan, "Hierarchical organization of cognition reflected in distributed frontoparietal activity," *Journal of Neuroscience*, vol. 32, no. 48, pp. 17373–17381, 2012.

[60] E. Fedorenko, J. Duncan, and N. Kanwisher, "Language-selective and domain-general regions lie side by side within broca's area," *Current Biology*, vol. 22, no. 21, pp. 2059–2062, 2012.

[61] M. Assem, I. A. Blank, Z. Mineroff, A. Ademoğlu, and E. Fedorenko, "Activity in the fronto-parietal multiple-demand network is robustly associated with individual differences in working memory and fluid intelligence," *Cortex*, vol. 131, pp. 1–16, 2020.

[62] S. Shashidhara, M. Assem, M. F. Glasser, and J. Duncan, "Task and stimulus coding in the multiple-demand network," *Cerebral Cortex*, vol. 34, no. 7, p. bhae278, 2024.

[63] N. Raz, A. Amedi, and E. Zohary, "V1 activation in congenitally blind humans is associated with episodic retrieval," *Cerebral Cortex*, vol. 15, no. 9, pp. 1459–1468, 2005.

[64] E. Diachek, I. Blank, M. Siegelman, J. Affourtit, and E. Fedorenko, "The domain-general multiple demand (md) network does not support core aspects of language comprehension: a large-scale fmri investigation," *Journal of Neuroscience*, vol. 40, no. 23, pp. 4536–4550, 2020.

[65] A. Amedi, A. Floel, S. Knecht, E. Zohary, and L. G. Cohen, "Transcranial magnetic stimulation of the occipital pole interferes with verbal processing in blind subjects," *Nature neuroscience*, vol. 7, no. 11, pp. 1266–1270, 2004.

[66] Y. Grodzinsky and A. Santi, "The battle for broca's region," *Trends in cognitive sciences*, vol. 12, no. 12, pp. 474–480, 2008.

[67] N. Geschwind, "The organization of language and the brain: Language disorders after brain damage help in elucidating the neural basis of verbal behavior.," *Science*, vol. 170, no. 3961, pp. 940–944, 1970.

[68] A. Martin, "The representation of object concepts in the brain," *Annu. Rev. Psychol.*, vol. 58, no. 1, pp. 25–45, 2007.

[69] M. L. Seghier, "The angular gyrus: multiple functions and multiple subdivisions," *The Neuroscientist*, vol. 19, no. 1, pp. 43–61, 2013.

[70] C. J. Price, "A review and synthesis of the first 20 years of pet and fmri studies of heard speech, spoken language and reading," *Neuroimage*, vol. 62, no. 2, pp. 816–847, 2012.

[71] E. Fedorenko, A. A. Ivanova, and T. I. Regev, "The language network as a natural kind within the broader landscape of the human brain," *Nature Reviews Neuroscience*, pp. 1–24, 2024.

[72] A. D. Friederici, "The brain basis of language processing: from structure to function," *Physiological reviews*, vol. 91, no. 4, pp. 1357–1392, 2011.

[73] E. Fedorenko and S. L. Thompson-Schill, "Reworking the language network," *Trends in cognitive sciences*, vol. 18, no. 3, pp. 120–126, 2014.

[74] I. Blank, N. Kanwisher, and E. Fedorenko, "A functional dissociation between language and multiple-demand systems revealed in patterns of bold signal fluctuations," *Journal of neurophysiology*, vol. 112, no. 5, pp. 1105–1118, 2014.

[75] T. Ness, V. J. Langlois, A. E. Kim, and J. M. Novick, "The state of cognitive control in language processing," *Perspectives on Psychological Science*, p. 17456916231197122, 2023.

[76] I. A. Blank and E. Fedorenko, "Domain-general brain regions do not track linguistic input as closely as language-selective regions," *Journal of Neuroscience*, vol. 37, no. 41, pp. 9999–10011, 2017.

[77] L. Wehbe, I. A. Blank, C. Shain, R. Futrell, R. Levy, T. von der Malsburg, N. Smith, E. Gibson, and E. Fedorenko, "Incremental language comprehension difficulty predicts activity in the language network but not the multiple demand network," *Cerebral Cortex*, vol. 31, no. 9, pp. 4006–4023, 2021.

[78] C. Lane, S. Kanjlia, A. Omaki, and M. Bedny, ""visual" cortex of congenitally blind adults responds to syntactic movement," *Journal of Neuroscience*, vol. 35, no. 37, pp. 12859–12868, 2015.

[79] S. Malik-Moraleda, D. Ayyash, J. Gallée, J. Affourtit, M. Hoffmann, Z. Mineroff, O. Jouravlev, and E. Fedorenko, "An investigation across 45 languages and 12 language families reveals a universal language network," *Nature Neuroscience*, vol. 25, no. 8, pp. 1014–1019, 2022.

[80] R. Cusack, A. Vicente-Grabovetsky, D. J. Mitchell, C. J. Wild, T. Auer, A. C. Linke, and J. E. Peelle, "Automatic analysis (aa): efficient neuroimaging workflows and parallel processing using matlab and xml," *Frontiers in neuroinformatics*, vol. 8, p. 90, 2015.

[81] S. B. Eickhoff, T. Paus, S. Caspers, M.-H. Grosbras, A. C. Evans, K. Zilles, and K. Amunts, "Assignment of functional activations to probabilistic cytoarchitectonic areas revisited," *Neuroimage*, vol. 36, no. 3, pp. 511–521, 2007.

[82] JASP Team, "JASP (Version 0.19.0)[Computer software]," 2024.

[83] C. R. Genovese, N. A. Lazar, and T. Nichols, "Thresholding of statistical maps in functional neuroimaging using the false discovery rate," *Neuroimage*, vol. 15, no. 4, pp. 870–878, 2002.

[84] J. R. Chumbley and K. J. Friston, "False discovery rate revisited: Fdr and topological inference using gaussian random fields," *Neuroimage*, vol. 44, no. 1, pp. 62–70, 2009.

[85] O. Collignon, G. Dormal, G. Albouy, G. Vandewalle, P. Voss, C. Phillips, and F. Lepore, "Impact of blindness onset on the functional organization and the connectivity of the occipital cortex," *Brain*, vol. 136, no. 9, pp. 2769–2783, 2013.

[86] G. Hickok and D. Poeppel, "The cortical organization of speech processing," *Nature reviews neuroscience*, vol. 8, no. 5, pp. 393–402, 2007.

[87] M. M. Churchland and K. V. Shenoy, "Temporal complexity and heterogeneity of single-neuron activity in premotor and motor cortex," *Journal of neurophysiology*, vol. 97, no. 6, pp. 4235–4257, 2007.

[88] H. Flor, T. Elbert, S. Knecht, C. Wienbruch, C. Pantev, N. Birbaumers, W. Larbig, and E. Taub, "Phantom-limb pain as a perceptual correlate of cortical reorganization following arm amputation," *Nature*, vol. 375, no. 6531, pp. 482–484, 1995.