Review Article

Cortical Areas Involved in Subjective Visual Vertical Perception: A Systematic Review

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Short running title: Cortical Areas Involved in Subjective Visual…

Highlights:
- The cortical areas involved in vertical perception are part of the vestibular network
- The vestibular network mainly includes the temporal, parietal and insular cortices
- The vestibular network mainly processes multi-sensory (cognitive and motor) inputs

ABSTRACT

Background and Aim: The information related to brain oscillation, head rotation and head orientation relative to gravity is obtained from the vestibular system. An important reference for upright posture and navigation is gravity-based vertical perception. Many studies have been conducted for the determination of cortical areas involved in Subjective Visual Vertical (SVV) perception in healthy people or patients with brain injuries. Their results have indicated an extensive and bilateral cortical area involved in SVV perception. The purpose of this review study is to investigate these cortical areas and their functional role.

Recent Findings: Neuroimaging studies in patients with brain injuries showed that multiple cortical areas have a role in SVV perception. These areas mainly include the occipital cortex, frontal cortex, posterior temporoparietal, temporo-occipital, parieto-occipital, superior temporal gyrus, inferior parietal lobe in

temporoparietal junction, posterior insula, cuneus, lingual gyrus, precuneus, ventral dentate nucleus, cerebellum, and brainstem.
Conclusion: The cortical areas involved in SVV perception are a part of the vestibular system, which is distributed bilaterally. These areas have a multi-sensory processing task and play a role in processing of cognitive and motor sensory information.
Keywords: Subjective visual verticality; vertical perception; cortex; vestibular network

Introduction
The information related to head oscillationtilts, and head orientation relative to gravity is obtained from the vestibular system [1]. An important reference for upright posture and navigation is the gravity-based subjective vertical which depends on visual, vestibular, and somatosensory data and vertical representation. This reference makes it possible to maintain the body posture relative to the surrounding environment (considering the gravity) and allows the body movement [2]. In studies conducted on healthy subjects for determining the cortical regions involved in Subjective Visual Vertical (SVV) perception, a large bilateral cortical network has been identified which includes regions such as the parietal cortex, occipital cortex, cuneus, lingual gyrus, precuneus, cerebellum, and brainstem [2-4]. In addition, neuro-imaging studies on patients with brain injuries have indicated multiple cortical regions related to the vertical perception [5-8]. Brain damage in areas such as the parietal cortex, posterior temporal cortex, inferior frontal gyrus, posterior insula, superior temporal gyrus, and Rolandic operculum can result in increased SVV deviations and incorrect vertical judgments [6]. All these brain regions are located in the vestibular-cortical network and are considered as a part of the vestibular system. The results of various studies on stroke patients and healthy people have confirmed this claim [1-4, 8]. Raiser et al. provided the detailed organization of connections between areas involved in vestibular information processing [1]. A study reported more vestibular symptoms in the right-hemisphere lesions compared to the left-hemisphere lesions, in addition to perturbations of vertical perception with more persistent symptoms [2]. However, Yelnik et al. found no relationship between perturbed SVV perception and the affected areas in the right or left hemisphere of stroke survivors [7]. In recent decades, the role of various sensory modalities in SVV perception has been extensively studied. However, little is known about the neural structures and functions involved in postural stability [3]. In this review study, we aimed to find the cortical areas involved in SVV perception and investigate the role of each region.

Methods
This is a systematic review study conducted according to the guidelines of the Standard Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [9]. The related studies published in English language from January 1990 to 2024 were searched in Scopus, PubMed and Web of Science databases using the following keywords: “subjective visual vertical” OR “subjective vertical perception” AND “vestibular” AND “vestibular network” AND “cortex” (Table 1). The reference section of the studies was also examined to find more articles for review. All types of studies including randomized clinical trials, observational studies, case studies and review articles were included. Only the studies that published in English language were included, and letters to the editor were excluded. Two authors independently assessed the relevance of studies to be included in the review in a standard and unblinded manner. Disagreements between them were solved by the third author. The information extracted from the studies included the year of publication, name of the first author, study area, study design, study population, the used instruments, study method, and results. Two authors assessed the quality of all included articles and ranked them in a descending order.

Results
Based on the initial search, 303 articles were found, and three articles were found based on the manual search of the reference section of the articles (Figure 1). After removing 99 duplicated studies, 207 articles remained. By reading the titles and abstracts, 114 irrelevant articles were removed. Of the remaining 93 articles, 69 were excluded after reading the full-text. Finally, 24 studies were selected for the review. There was no case report or animal study. They all were retrospective studies. There were two review studies, 14 randomized clinical trials, and eight case series. They had good to moderate quality.

Discussion

Cortical areas involved in subjective visual vertical perception

Neuroimaging studies on brain-damaged patients showed that multiple cortical areas in different lobes are involved in SVV perception [2]. Considering the results of various studies, these regions include occipital cortex, frontal cortex, posterior temporoparietal cortex, temporal-occipital cortex, parietal-occipital cotex, superior temporal gyrus, inferior parietal lobe in the Temporoparietal Junction (TPJ), posterior insula, cuneus, lingual gyrus, precuneus, dentate nucleus (ventral), cerebellum, and brainstem [2, 4, 5, 10-14]. Considering this large cortical network, it can be said that the neurologic basis of postural stability requires constant representation or updating of the perception of verticality [2]. The role of these regions, which are activated during SVV perception, has been shown in studies assessed the SVV perception in stroke survivors [5, 8, 10]. Moreover, it has been shown that patients with damage to their partial cortex and posterior temporal cortex [5, 10] or the posterior insula [13, 14], have incorrect vertical judgments. Lopez et al. used high-density electrical neuroimaging in their study and showed a potential map related to SVV judgment in the right temporal-occipital cortex, as well as a bilateral map in the parietal-occipital and temporal-occipital cortices [4]. Furthermore, after damage to the TPJ, verticality perception deviation has been reported [5, 10]. The role of inferior peduncle has also been reported in subjective visual vertical perception [15]. Activity in the anterior region of the cerebellum and the midbrain can be a sign of activity in visuospatial/cognitive loops including the ventral dentate nucleus [11, 12]. The high overlap of brain regions involved in SVV perception in healthy people with the regions reported in studies on verticality perception deviation is an important finding with high clinical value.

Functional role of cortical areas involved in subjective visual vertical perception

Temporal-occipital and parietal-occipital regions, cerebellum, and brainstem are involved in body representation [16], balance control [17], and spatial navigation [18]. The cuneus and lingual gyrus are involved in orientation discrimination tasks [19]. The precentral gyrus (Broadmann Region 6) as a part of the premotor cortex, has a role in planning or organizing specific postural movements [20, 21]. This region plays an important role in the transmission of vestibular signals to the brain in primates [22], which acts as part of a direct locomotor pathway [23]. As part of the sensorimotor system, the posterior parietal cortex (extending behind postcentral gyrus) processes the multisensory inputs used in motor responses. In addition, it probably participates in the processing of gravity perception data related to upright posture [24]. The insula is known as a region with multisensory processing ability in the brain. Its posterior part has a multimodal area that receives inputs from various sensory systems. The data related to the vestibular system is a remarkable part of such convergent inputs [25, 26]. In the temporal lobe, the inferior and middle temporal gyri are involved in processing of complex and often emotional stimuli, in addition to the subjective rotation and spatial discrimination [26].

In the frontal lobe, the cognitive control in visual motor timing and preparation for movement is the responsibility of the medial superior frontal cortex [26]. Various studies demonstrated the important role of the Anterior Cingulate Cortex (ACC) in SVV perception [2, 4, 8]. Action monitoring and error signal detection are also among the roles of ACC [27]. According to Adkin et al., the error signal refers to the difference between the actual state and the expected state of balance during transient balance disturbances [28]. Increased activity in the frontocentral region and/or ACC during balance assessment for detecting postural instability has been reported in various studies [29, 30]. In fMRI studies, the increased ACC activities has been reported during successful recognition of postural instability [31].

Regarding the role of brain oscillations in SVV perception, Hülsdünker et al. [27] and Jafari et al. [8] emphasized the important role of parietal and frontal beta-band oscillations in balance maintenance. Since the functional role of beta-band oscillations is not yet well understood [32], it is difficult to investigate their role in vestibular data processing. Beta-band oscillations are probably involved in the coupling of vestibular sensory inputs with oculomotor outputs [33]. These oscillations are related to sensorimotor functions and representation of the “idling rhythm” of the motor system [34]. A recent study suggested the association of beta-band oscillations with the maintenance of the current motor state [32]. Based on motor and cognitive control tasks, it is possible that the beta-band oscillations are involved in sending information about the status quo [33].

Electrophysiological studies showed that vestibular outputs to frontal regions play a role in controlling movement and oculomotor functions [35, 36]. Activities in the frontal cortex can play a role in the control of eye movements caused by vestibular stimulation [37], and it is consistent with this theory that vestibular data processing in the frontal cortex is responsible for controlling some aspects of the vestibulo-ocular reflex, the production of saccades, and smooth pursuit eye movements [36]. The precuneus in the parietal lobe plays a role in various cognitive functions such as mental and spatial perception and self-referential processing [38]. Other studies have also shown the role of this region in understanding self-motion, imagining the movement of the whole body, and mental navigation [39, 40]

Conclusion

The cortical areas involved in Subjective Visual Vertical (SVV) perception are a part of the vestibular system, which is distributed bilaterally. These areas have a multi-sensory processing task and play a role in processing cognitive and motor sensory information. Regarding the role of the cerebral cortex in different aspects of spatial perception, human studies have demonstrated an extensive cortical network distributed mainly in the temporal, parietal and insular cortices. The important role of information about the body posture relative to the surrounding environment should not be neglected, since it affects all movement functions. Regarding the SVV perception, the higher-order neural mechanisms can resolve differences and ambiguities in understanding the reference frames of different senses in integrating different sensory data.

Ethical Considerations

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Authors' contributions

In writing and editing this article, the contribution of the authors is equal.

Conflict of interest

There is no conflict of interest.

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Table 1. Search strategy according to the participants, intervention, comparator, outcome and time protocol

Frame	Participants	Intervention	Comparator	Outcome	Time
Mesh terms	Any	Vertical perception	None	Cortical activity	Any
Search	PubMed: (((vertical perception) OR (subjective visual vertical)) AND ((vestibular) OR (vestibular network))) AND (cortex) Scopus: ((TITLE-ABS-KEY (vertical perception) OR TITLE-ABS-KEY (subjective visual vertical))) AND ((TITLE-ABS-KEY (vestibular) OR TITLE-ABS-KEY (vestibular network))) AND (TITLE-ABS-KEY (cortex)) Web of Science: https://www.webofscience.com/wos/woscc/summary/accf5916-f543-43db-ac83-d51ad90ff489-be1316c5/relevance/1 accessed on 30 January 2024				
Exclusion Criteria	irrelevant title or abstract, irrelevant full-text, editorial, reviews, meta-analysis, neonatal studies, experimental/non-human studies, non-English studies, responses not including vertical perception				
Sources	Databases (PubMed, Scopus, Web of Science) Reference list				
Time limits	The search period: any until July 2023			Last search: 30 November 2023	

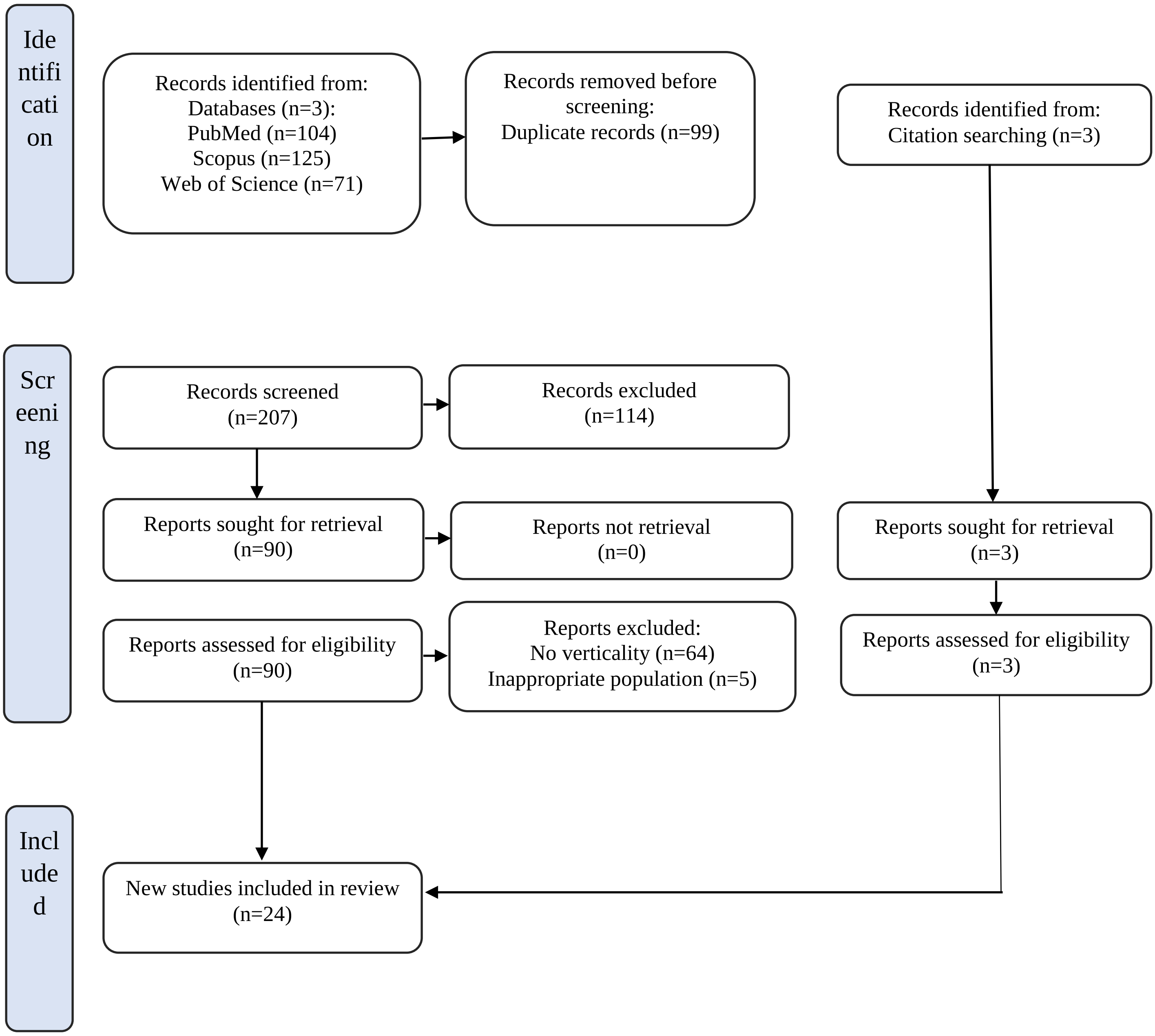

Figure 1. Schematic flowchart of our literature search