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MULTIMODAL AND MULTISPATIAL DEFICITS OF VERTICALITY PERCEPTION IN HEMISPATIAL NEGLECT

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Abstract—Recent evidence suggests that patients with left-sided visuospatial neglect often show deviations in their visual and haptic perception of verticality in the frontal and sagittal plane. However, little is known about the multimodality of these impairments and the relationship between deviations in the frontal and the sagittal plane. Moreover, no previous study has combined investigations of verticality judgments in both modalities and both spatial planes within the same sample of subjects using the same apparatus. Thus, the aim of the present study was to investigate both subjective visual vertical (SVV) and subjective haptic vertical (SHV) judgments in the frontal and the sagittal plane in right-brain-damaged patients with visuospatial neglect (n=16), right-brain-damaged patients without neglect (n=18) and age-matched healthy individuals (n=16) using the same testing device for all tasks. This allowed for direct comparisons of visual vs. haptic and frontal vs. sagittal verticality judgments. Neglect patients showed significant counterclockwise tilts in their SVV and SHV judgments in the frontal plane as well as marked backward (upper end of the rod towards the observer) tilts in the sagittal plane. In contrast, right-brain-damaged patients without neglect and healthy individuals showed no marked deviations in the frontal plane, but small forward (upper end of the rod away from the observer) tilts in the sagittal plane. Moreover, neglect patients showed significantly higher unsigned errors in all tasks. These results demonstrate multimodal and multispatial deficits in the judgment of verticality in patients with visuospatial neglect which are most likely due to an altered representation of verticality caused by lesions of brain areas related to multisensory integration and space representation in the right temporo-parietal cortex.

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Abbreviations: BJLOT, Benton Judgment of Line Orientation test; M, mean; SD, standard deviation; SEM, standard error of the mean; SHV, subjective haptic vertical; SV, subjective vertical; SVH, subjective visual horizontal; SVV, subjective visual vertical.

Key words: neglect, visual, haptic, subjective vertical, multisensory, 3D space.

BRAIN DAMAGE, SPATIAL ORIENTATION AND HEMINEGLECT

Reading the clock is an essential part of our everyday activities. However, imagine not being able to judge the exact position of the clock hands and therefore never being on time. Or imagine, all the paintings on your wall are crooked, but you don't recognize it. Such impairments frequently occur in patients with right-hemispheric brain lesions after stroke. Their perception of vertical, horizontal or oblique lines (such as clock hands or picture frames) is often impaired. A method commonly used to measure this deficit is the assessment of the subjective visual vertical (SVV) or horizontal (SVH). Here, a movable rod is rotated in the frontal (roll) plane, until the patient indicates that it is aligned with the physical vertical or horizontal. Bender and Jung (1948) were among the first who systematically studied the SVV and SVH in healthy and brain-damaged individuals. In the latter group, they found contraversive deviations larger than 2° from the veridical vertical in case of a frontal or parietal, but not occipital lobe lesion. Several subsequent studies confirmed these findings showing that patients with right-hemispheric brain lesions show a contraversive tilt of their SVV in the frontal plane (Kerkhoff and Zoelch, 1998; Kerkhoff, 1999; Saj et al., 2005a), and a similar or even larger tilt of the subjective haptic vertical (SHV; Kerkhoff, 1999; Funk et al., 2010a). Furthermore, these deficits seem to be multimodal as the tilt in the visual modality is significantly correlated with that in the haptic modality (Kerkhoff, 1999; Perennou et al., 2008), and with postural deficits in patients with right parietal lesions (Perennou, 2006).

Lesion analyses in patients with a contraversive SVV tilt in the frontal plane identified the posterior insula, the human homologue of the monkey parieto-insular vestibular cortex (Guldin and Grusser, 1998), as one crucial lesion site (Brandt et al., 1994). However, recent research revealed that also the right parietal cortex, which is considered as a key area for multimodal space integration and representation (for review, see Andersen et al., 1997) is critical for multimodal axis tilts (Perennou et al., 2008).

Notably, these lesion sites are adjacent to and are partly overlapping with those anatomical regions associated with visual hemineglect, namely the insula (Karnath et al., 2004), the temporo-parietal junction (Vallar and Perani, 1986), the superior temporal gyrus (Kar-

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nath, 2001; Karnath et al., 2004), posterior parietal (Mesulam, 1999) and intraparietal cortices (Mort et al., 2003; Verdon et al., 2010), the thalamus and basal ganglia (Vallar and Perani, 1986; Karnath et al., 2004). Given the anatomical proximity, it is not surprising that neglect patients show visuospatial deficits in the perception of axis orientation judgments (Kerkhoff and Zoelch, 1998; Yelnik et al., 2002; but see Johannsen et al., 2006 for slightly diverging results in neglect patients with pusher symptoms), in addition to their well-known contralesional deficits in visual search, cancellation and drawing tasks. Moreover, a close association between visuospatial neglect and postural disorders has been repeatedly found (Saj et al., 2005b; Perennou, 2006), and an association between disturbances of the subjective vertical (SV) and poor postural recovery was shown (Bonan et al., 2007).

Current theories of gravity processing hypothesize that the representation of verticality is based on the integration of visual, vestibular and somatosensory input (Brandt and Dieterich, 1999), which is assumed to depend crucially on the vestibular cortex (Bronstein, 1999; Mittelstaedt, 1999). Consequently, impaired integration of sensory signals due to brain lesions in the above-mentioned brain areas, leads to asymmetrical processing of sensory input resulting in perturbed spatial representations (Funk et al., 2010a). Modulation of the SV due to asymmetrical sensory input was shown to be inducible in healthy individuals by changes of posture (Luyat and Gentaz, 2002) with reduced precision of vertical judgments during body tilt or via galvanic vestibular stimulation with SV deviations towards the anode (Mars et al., 2001). In neglect patients lateral head tilts modulated SV judgments in direction of the head inclination (Funk et al., 2010b) and changes of posture resulted in larger SV deviations in supine as compared to an upright body position (Funk et al., 2010a). Furthermore galvanic vestibular stimulation reduced the counterclockwise SV tilts of neglect patients during left-cathodal stimulation (Saj et al., 2006). Together, these studies show that manipulations of sensory input (via postural changes or galvanic vestibular stimulation) affect SV judgments in general. However, patients with visuospatial neglect seem to be much more susceptible to such manipulations than healthy subjects or non-neglecting patients. These results have been interpreted in favour of an unstable and tilted representation of verticality in neglect patients (Funk et al., 2010b).

However, verticality perception does not only include the frontal (roll) plane, but also the sagittal (pitch) plane (see Fig. 1A). Up to now, only few studies have investigated the perception of the SV in the sagittal (pitch) plane in patients with brain lesions. Saj et al. (2005a) found that neglect patients showed a backward tilt of the SVV (upper end of the rod towards the observer), in addition to a counterclockwise SVV tilt in the roll plane. Moreover, a greater individual variability in SVV judgments in the pitch plane compared to the roll plane was shown, indicating that the task is more difficult in pitch than in roll. Furthermore, the SVV judgments in pitch and roll were not intercorrelated, suggesting independent processing of verticality in these two spatial planes. Funk et al. (2010a) extended this finding to the haptic modality showing backward tilts in SHV judgments of neglect patients in the pitch plane. Moreover, a larger tilt was observed in patients with severe as compared to moderate visuospatial neglect, suggesting a close relationship to neglect severity. In contrast to Saj et al. (2005a), SHV values in roll and pitch were highly intercorrelated in the study of Funk et al. (2010a), indicating comparable results in both spatial planes.

One limitation of the study of Saj et al. (2005a) was that patients touched the rod for visual SVV adjustments to the subjective vertical. Thus, this task was not purely visual but rather a combined visual-haptic SV task which does not allow for a direct comparison of the two modalities (haptic, visual). Therefore, one aim of the present study was to investigate SVV judgments in right-brain damaged patients by excluding haptic input cues for verticality. Furthermore we sought to analyze the relationship between visual and haptic SV judgments in pitch and roll. Thus, the experiment presented here, investigated for the first time, both SVV and SHV judgments in pitch and roll in right-brain-damaged patients with neglect, right-brain-damaged patients without neglect and age-matched healthy individuals using a novel testing device for all these tasks in order to allow direct comparisons between modalities and spatial planes.

Based on previous findings (Saj et al., 2005a; Funk et al., 2010a) the following hypotheses were formulated:

(1) Neglect vs. non-neglect: Right-brain damaged patients with left visuospatial neglect show larger directional errors as well as unsigned errors of the SVV and SHV in pitch and roll than right-brain-damaged patients without neglect or healthy individuals.
(2) Direction of tilts: SVV and SHV tilts of neglect patients, but not of patients without neglect or healthy controls, are directed counterclockwise in the roll plane and backward in the pitch plane.
(3) Modalities: With respect to the two modalities, we expected comparable deviations in the visual and haptic modality and significant intercorrelations based on previous findings (Kerkhoff, 1999).
(4) Roll vs. pitch plane: Concerning the relationship between SVV in roll and SVV in pitch as well as between SHV in roll and SHV in pitch we had no specific predictions, since there were both observations of correlated deviations between the SHV in pitch and roll (Funk et al., 2010a), as well as dissociated impairments of the SVV in pitch and roll (Saj et al., 2005a).

EXPERIMENTAL PROCEDURES

Participants

Sixteen patients (nine males, seven females) with right-hemispheric vascular brain lesions and left visual neglect as indicated by six clinical neglect tests (see “Assessment of visual field, visual neglect and visuospatial perception,” below) with a mean age of 71 years (range: 52–86) participated in the study. Furthermore, 18