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Visual contribution to human standing balance during support surface tilts

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ABSTRACT

Visual position and velocity cues improve human standing balance, reducing sway responses to external disturbances and sway variability. Previous work suggested that human balancing is based on sensory estimates of external disturbances and their compensation using feedback mechanisms (Disturbance Estimation and Compensation, DEC model). This study investigates the visual effects on sway responses to pseudo-random support surface tilts, assuming that improvements result from lowering the velocity threshold in a tilt estimate and the position threshold in an estimate of the gravity disturbance. Center of mass (COM) sway was measured with four different tilt amplitudes, separating the effect of visual cues across the conditions 'Eyes closed' (no visual cues), '4 Hz stroboscopic illumination' (visual position cues), and 'continuous illumination' (visual position and velocity cues). In a model based approach, parameters of disturbance estimators were identified. The model reproduced experimental results and showed a specific reduction of the position and velocity threshold when adding visual position and velocity cues, respectively. Sway variability was analyzed to explore a hypothesized relation between estimator thresholds and internal noise. Results suggest that adding the visual cues reduces the contribution of vestibular noise, thereby reducing sway variability and allowing for lower thresholds, which improves the disturbance compensation.

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1. Introduction

Human balancing during upright stance is more stable with eyes open than with eyes closed (Horak & Macpherson, 1996). Uncertainties remain how the visual cues are integrated in the balance control mechanism and which sensorimotor mechanisms are involved. The current study aims to understand the sensory integration of visual cues in the stabilization of the body center of mass (COM) during support surface tilts and does not consider other aspects, such as a head stabilizing effect in the presence of visual cues (Dietz, Trippel, Ibrahim, & Berger, 1993; De Nunzio, Nardone, & Schieppati, 2005; Mergner, Schweigart, Fennell, & Maurer, 2009). The study investigates the effect of visual cues in a stationary visual scene, as moving visual scenes involve cognitive mechanisms that may mask the stabilizing effect of visual cues (Nashner & Berthoz, 1978; Bronstein, 1986; Guerraz, Thilo, Bronstein, & Gresty, 2001; Blümle, Maurer, Schweigart, & Mergner, 2006). In a stationary visual scene, two visual effects on the COM stabilization stand out. One is the reduction of sway variability in unperturbed stance (spontaneous sway) and the other the reduced sway response amplitudes that are evoked by external disturbances such as support surface tilts. The reduction of sway amplitudes is here considered as an increase in stability, as the body remains closer to the desired upright position, which, however, is not necessarily a valid criterion in other contexts (e.g., pathological conditions).

Spontaneous sway during unperturbed stance is reduced by a factor of about two when viewing a stationary visual scene as compared to conditions without visual space reference (Romberg, 1846; Edwards, 1946; Paulus, Straube, & Brandt, 1984). Model based simulations suggest that spontaneous sway results from internal noise in the balance control mechanism (Peterka, 2000; Maurer & Peterka, 2005), where the resulting sway is determined by the noise source (sensory noise, motor noise, etc.), the neural control mechanism and its dynamics, and the biomechanics of the standing human. The vestibular system appears to be a major noise source (Mergner, 2007; Van der Kooij & Peterka, 2011). In contrast, the visual signals are assumed to contain relatively little noise (Dokka, Kenyon, Keshner, & Kording, 2010; van Beers, Sittig, & Denier van der Gon, 1998).

Although variability in human motor control can be functionally beneficial (Davids, Glazier, Araujo, & Bartlett, 2003; van Emmerik & van Wegen, 2002), internal noise is mostly thought to be disadvantageous for human sensorimotor function (Wolpert & Ghahramani, 2000). Noise has, for example, been discussed to cause an increase in feedback loop gain in the balance control mechanism of Parkinson's disease patients, evoking a resonant behavior, which largely deteriorates stance stability (Maurer, Mergner, & Peterka, 2004). The general tendency of the sensorimotor system to reduce variability (Dokka et al., 2010; Franklin & Wolpert, 2011) could explain the reduction of spontaneous sway in the presence of a visual space reference. The underlying assumption is that low noise visual cues reduce internal noise by replacement of, or fusion with high noise vestibular cues.

Research using stroboscopic illumination showed that stroboscopic frequencies of about 3 Hz reduce spontaneous sway as compared to eyes closed conditions (Amblard, Crémieux, Marchand, & Carblanc, 1985). Increasing the stroboscopic frequency gradually further reduces spontaneous sway, with sway becoming similar to that during continuous illumination when the stroboscopic frequency reaches 32 Hz (Paulus et al., 1984). During stroboscopic illumination of about 4 Hz strobe frequency and below, the visual system can resolve displacement only as 'broken motion' (i.e., a change in position information rather than velocity; Croft, 1971; Wertheimer, 1912), while an increase in stroboscopic frequency leads to a gradual addition of visual velocity cues (Paulus et al., 1984).

The effects of visual position and velocity cues on the closed loop balance control mechanism cannot be identified from spontaneous sway measures. The reason is that the properties of the underlying noise are unknown. This is different when applying known external disturbances, which allow distinguishing between the noise and the response of the balance control mechanism to the stimulus (Van der Kooij, van Asseldonk, & van der Helm, 2005). A previous study from our laboratory investigated combined stroboscopic illumination and support surface tilt to analyze the effect of visual position and velocity cues on the dynamics of the control system (Assländer, Hettich, Gollhofer, & Mergner, 2013). An unpredictable pseudo-random sequence was used as tilt stimulus, where the Low frequency