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Size estimates of action-relevant space remain invariant in the face of systematic changes to postural stability and arousal

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ABSTRACT

Perceptual estimates of action-relevant space have been reported to vary dependent on postural stability and concomitant changes in arousal. These findings contribute to current theories proposing that perception may be embodied. However, systematic manipulations to postural stability have not been tested, and a causal relationship between postural stability and perceptual estimates remains to be proven. We manipulated postural stability by asking participants to stand in three differently stable postures on a force plate measuring postural sway. Participants looked at and imagined traversing wooden beams of different widths and then provided perceptual estimates of the beams' widths. They also rated their level of arousal. Manipulation checks revealed that the different postures resulted in systematic differences in body sway. This systematic variation in postural stability was accompanied by significant differences in self-reported arousal. Yet, despite systematic differences in postural stability and levels of arousal perceptual estimates of the beams' widths remained invariant.

1. Introduction

Humans maintain postural stability, amongst other things, by means of visual input. Visual disturbances such as reduced illumination levels (e.g., Edwards, 1946), motion parallax (e.g., Bronstein & Buckwell, 1997) and optic flow (e.g., Bardy, Warren, & Kay, 1999; Lee & Aronson, 1974) lead to postural imbalance, as evidenced by increased postural sway. In the light of recent developments of embodied theories of cognition (e.g., Barsalou, 2008) and perception (e.g., Proffitt, 2006), researchers have come to reason (and reported evidence for the claim) that the relationship between vision and postural control may not be unidirectional, but bidirectional in nature. If true, this means that changes to postural stability should also evoke changes to the visual perception of the environment.

As for the impact of postural stability on cognitive functions that require visual spatial memory, about 30 years ago Kerr, Condon, and McDonald (1985) showed that perturbations to postural stability, induced by means of differently stable postures such as the Tandem Romberg stance (a heel to toe standing position), indeed affected spatial memory performance. This effect was highly selective as postural stability only interfered with spatial memory tasks but not with non-spatial memory tasks. Based on these findings, the authors concluded that "cognitive spatial processing may rely on neural mechanisms that are also required for the regulation of posture" (Kerr et al., 1985, p. 617).

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Recently, also the direct impact of postural stability on visual perception has been scrutinized. Geuss, Stefanucci, de Benedictis-Kessner, and Stevens (2010) examined whether changes to postural stability modulated visual size estimates of action-relevant objects. In their first experiment participants either maintained a balanced or an unbalanced position (by means of standing on a balance board). In both conditions participants were then presented with wooden beams which they had to imagine walking across, after which they provided width estimates of the beams by means of a visual matching task. The imaging instruction was included because embodied perception approaches argue that the impact of psychological and physiological states on visual perception is prone to occur for action-relevant objects that people (at least) intend to interact with. More specifically, it is argued that perceptual estimates of the environment are modulated by the costs associated with acting on it (e.g., Proffitt, 2006). Following this line of reasoning, Geuss et al. hypothesized that an unbalanced posture would increase the perceived costs of the imagined action (i.e., walking over the beam), and hence would result in smaller beam estimates than when in a balanced (i.e., stable) posture. In agreement with their hypothesis, results showed that participants judged the beams to be wider when they maintained a stable position on a stabilized balance board than when standing in an unbalanced position on a rotating balance board. This indicated that visual estimates of the environment are affected by postural stability.

In a series of follow-up experiments (Exp. 2–5B), Geuss et al. (2010) examined potential mediators such as arousal and attention. To this end, they used various manipulations such as increasing arousal by means of jogging, counting backwards or using arousing pictures from the International Affective Picture System (IAPS; Lang, Bradley, & Cuthbert, 1999). The collective results of these experiments indicated that increased levels of arousal moderated width estimates of the beams. Therefore, the authors concluded that physical balance, through arousal, modulates size estimates.

However, Geuss et al. (2010) did not systematically manipulate postural stability, but instead applied a dichotomous distinction between a balanced and an unbalanced posture without actually measuring the degree of postural sway. The authors recognized this themselves and called for research that manipulated sway to test the notion that "width estimates decrease as postural sway increases" (Geuss et al., 2010, p. 1900). The aim of the current study was to put this hypothesis to experimental scrutiny. To this end, we systematically manipulated postural stability by asking participants to stand in three static postures, differing in stability (i.e., a bipedal stance, a tandem stance, and a single-leg stance) on a force plate measuring postural sway. Similar to Geuss et al. (2010), participants were instructed to look at wooden beams of different widths and to imagine traversing them. Participants then provided perceptual estimates of the width of the beams, and additionally subjectively rated their levels of arousal.

2. Method

2.1. Participants

Twenty female participants[1] (mean age = 22.7 years; SD = 2.2) volunteered to take part in the experiment. Participants had normal or corrected-to-normal vision and were naive as to the purpose of the study. All participants provided informed consent prior to experimentation, and the experiment was approved by the ethical committee of the Faculty of Human Movement Sciences, VU University Amsterdam.

2.2. Apparatus

Closely following the methods of Geuss et al. (2010), four wooden beams of equal length (122.5 cm) but different widths (1.7 cm, 3.6 cm, 8.4 cm, and 13.5 cm) were used in this experiment. The beams were placed on top of two vertically oriented crates (length: 29.7 cm; width: 23.8 cm; height: 40 cm), right in front of the participant. That is, the length of the beam extended directly in front of the participant's position with the closest part of the beam being at a distance of 97 cm from the participant's position.

To measure postural sway, participants stood on a custom-made strain gauge force plate (length: 108 cm; width: 108 cm; height: 16 cm) that sampled at a frequency of 100 Hz. The force plate consisted of eight force sensors. Four sensors measured the forces in the z direction, two in the x direction and two in the y direction. These 8 signals were automatically converted into a center-of-pressure (COP) time series, separate for the medial–lateral (ML) and the anterior–posterior (AP) direction. The foot positions were marked on the force plate to ensure consistent positions across participants and the different postural conditions.

To gather participants' width estimates, white sheets of paper (A4, landscape) with a black horizontal line in the middle (stretched over the entire width of the sheet) were prepared.

2.3. Procedure

Upon arrival, participants were welcomed, informed about the details of the experimental session, and then asked to sign the consent form. Next they were kindly requested to inform the experimenters about their preferred leg, take off their shoes, step onto the force plate, and position themselves, i.e., their feet at the positions marked on the force plate.

[1] This sample size is equal to the sample size in the balance manipulation experiment (Exp. 1) in Geuss et al. (2010).

Participants were instructed to adopt one of three different stance conditions: (i) a bipedal stance (with the two feet next to each other), (ii) a tandem stance (performed in a heel-to-toe position with the preferred leg behind), and (iii) a single-leg stance, on the preferred leg. These stance conditions were supposed to systematically decrease postural stability (i.e., in the order: i–ii–iii). Applying a within-subjects design, participants performed the three different stance conditions eight times each. On each trial they remained in the respective stance for 20 s. The eight trials per stance condition were blocked, and block order was counterbalanced across participants. On each trial, and independent of the stance condition, participants were instructed to maintain an as stable as possible stance, and to stand with their arms crossed above the chest and the hands put on their shoulders. To measure postural stability, at the start of each trial the experimenter started the COP measurements that lasted for the full 20 s during which participants remained in the prescribed stance. During this time interval, participants were further instructed to focus on (i.e., look at) the presented beam and not to speak. Immediately after the 20 s had passed, participants were asked to re-engage in a comfortable bipedal stance, look at the beam and to imagine traversing, that is, walking across the observed beam. When participants indicated that they had created a vivid mental image of traversing the beam, they were asked to provide estimates of the width of the present beam. To this end, an experimenter positioned herself next to the participant (i.e., in front, slightly off to the right so as not to occlude vision to the beam); she provided the participant with a pen and held up a clipboard with the white sheet of paper next to the participant. The participant was asked to provide her width estimate by drawing two vertical lines crossing the horizontal black line; the distance between the two lines representing the width estimate of the beam. Participants were allowed to look back and forth between the beam and the sheet until they were confident to judge each beam's width. Once the participants had provided their estimate, the trial was finished, and they were asked to put on goggles occluding vision so that they were blind toward the change of the wooden beam for the upcoming trial. This procedure was repeated eight times for each stance condition. The beams were presented in pseudo-random order, such that the same beam was never presented twice in succession. At the end of each block of eight trials (i.e., after providing the last beam width estimate of each stance condition), participants rated subjective levels of arousal on a scale from 1 (not aroused at all) to 7 (extremely aroused; see Geuss et al., 2010, Exp. 5A). At the end of the experiment, to rule out demand effects or experimenter bias effects, participants were questioned whether they could infer the hypothesis of the experiment[2]. Finally, demographic information was gathered and participants were debriefed about the real purpose of the experiment. The entire procedure lasted about 45 min.

2.4. Data analysis

To determine whether our experimental manipulation (i.e., the three different stances) indeed caused systematic changes in postural stability, we first ran two separate analyses of variance (ANOVAs) on the Standard Deviation (SD; an indicator of the amount of postural sway) of the COP in the medial–lateral (ML) and the anterior–posterior (AP) direction of postural sway (in the remainder of the paper referred to as SD [COP ML] and SD [COP AP]). The respective COP data was processed and analyzed with Matlab 7.12.0 (Math Works). The signal was low-pass filtered at 5 Hz with a 2nd order Butterworth filter. The first and last 2.5 s of each signal were removed to rule out any non-representative sway fluctuations at the beginning and end of each trial.

Next we checked whether our stance manipulations also caused changes in subjective ratings of arousal. As previous studies have used the same arousal scale and treated the data as a continuous measure (e.g., Geuss et al., 2010), for reasons of better comparability we decided to follow the same route. To compare the effect of the three different standing postures on subjective arousal ratings, we ran an ANOVA on the mean arousal scores per condition[3]. Post-hoc, Bonferroni corrected pairwise comparisons were administered to further determine differences between means.

Next, we ran the main analysis of interest. That is, we examined whether perceptual estimates of the beams' widths varied depending on differences in postural stability. To this end, we ran a 3 (stance condition: bipedal, tandem, single-leg) by 4 (four beam widths) ANOVA on the mean width estimates. In case Mauchly's test revealed a violation of the sphericity assumption, Greenhouse–Geisser corrections were applied. The effect sizes were calculated using partial eta squared values (η_p^2) and the alpha level for significance was set at .05.

3. Results

3.1. Manipulation checks

Results showed that the stance manipulations caused significant differences in postural stability. The ANOVA on the SD [COP ML] revealed a significant effect for stance condition, $F(1.449, 27.528) = 40.210$, $p < .001$, $\eta_p^2 = 0.679$. As illustrated in Fig. 1A, post hoc pairwise comparisons revealed that the mean SD [COP ML] of the bipedal stance was significantly lower (indicating higher postural stability) than the tandem stance ($p < .001$) and the single-leg stance ($p < .001$), and that the

[2] There was only one participant who correctly inferred the hypothesis that a less stable posture should result in smaller width estimates. As inspections of this individual's width estimates did not show any inconsistencies or differences to the data of the other 19 participants, we did not see any reason to remove the participant's data, so we included the data in all analyses.

[3] Since our arousal scores are ranked on an ordinal scale, we decided to also run the same comparisons with non-parametric tests (i.e., a Friedman's ANOVA and as follow-ups Wilcoxon signed-rank tests). These analyses yielded the same significant results as the parametric test.

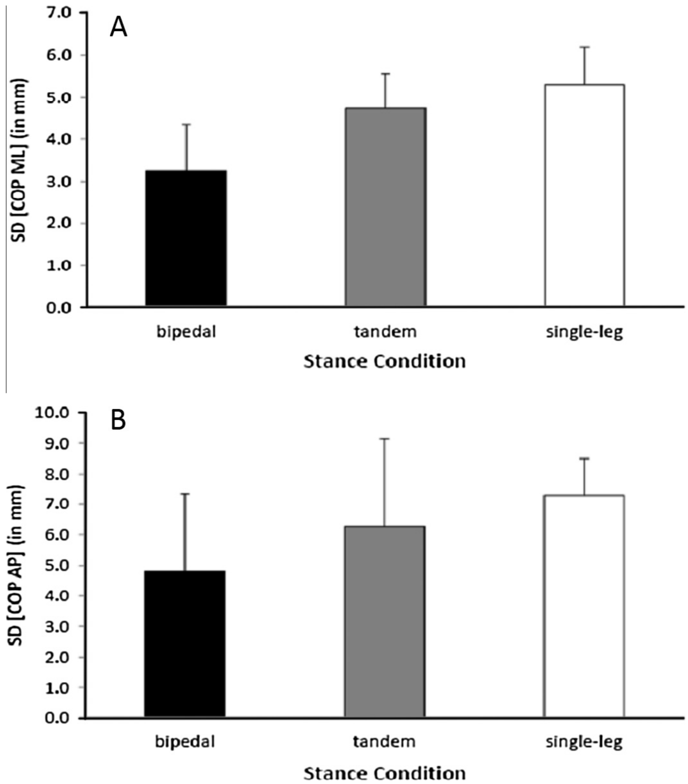

Fig. 1. Mean SD [COP ML] (1A) and mean SD [COP AP] (1B) values across the three different stance conditions. Bars indicate standard deviations (SD).

tandem stance had significantly lower SD [COP ML] values than the single-leg stance ($p = .011$). The ANOVA[4] on the SD [COP AP] also revealed a significant effect for stance condition, $F(2,38) = 7.015$, $p = .003$, $\eta_p^2 = .270$. As illustrated in Fig. 1B, post hoc pairwise comparisons revealed that the mean SD [COP AP] of the bipedal stance was significantly lower than the single-leg stance ($p = .005$), and that the tandem stance had significantly lower SD [COP AP] values than the single-leg stance ($p = .048$). For the anterior–posterior direction there was no difference between the bipedal and the tandem stance. Together, these analyses confirm that postural stability indeed systematically decreased from the bipedal stance to the tandem stance to the single-leg stance.

Results further revealed that the stance condition manipulations resulted in significant differences in subjective ratings of arousal. The ANOVA on the arousal scores revealed a significant effect for stance condition, $F(2,38) = 113.013$, $p < .001$, $\eta_p^2 = 0.856$. As illustrated in Fig. 2, pairwise comparisons revealed that arousal scores were lower in the bipedal stance than in the tandem stance ($p = .002$) and the single-leg stance ($p < .001$), and that in the tandem stance participants felt significantly less aroused than in the single-leg stance ($p < .001$). Thus, the systematic decrease in postural stability was accompanied by a significant increase in subjective ratings of arousal, thereby confirming that our stance condition manipulations resulted in the desired effects.

3.2. Size estimates

A 3 (stance condition: bipedal, tandem, single-leg) by 4 (actual beam widths) ANOVA on the mean width estimates revealed no significant main effect for stance condition, $F(2,38) = .440$, $p = .647$, $\eta_p^2 = .023$. Means for all conditions are presented in Fig. 3. As expected, there was a significant main effect of beam, $F(1.364,25.916) = 802.733$, $p < .001$, $\eta_p^2 = 0.977$, indicating that with an increase in actual width, beams were also estimated to be wider. Importantly, there was no significant stance condition by beam interaction, $F(2.720,51.684) = .277$, $p = .823$, $\eta_p^2 = .014$. It follows that width estimates were not affected by differently stable stances.

When we performed the same analysis on the mean relative estimating errors (actual width *minus* estimated width) per beam width and condition the same pattern of results emerged.

[4] Despite the fact that the data was not normally distributed, we decided to run and report the ANOVA for the SD [COP AP] based on the raw data, as the same analysis on log10-transformed data revealed the same significant findings.

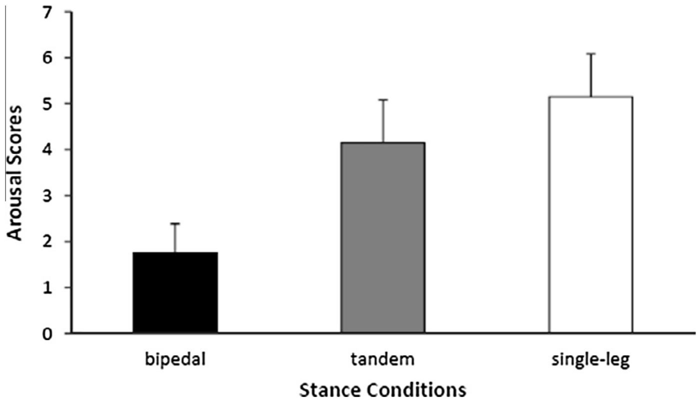

Fig. 2. Mean subjective ratings of arousal across stance conditions. Bars indicate standard deviations (SD).

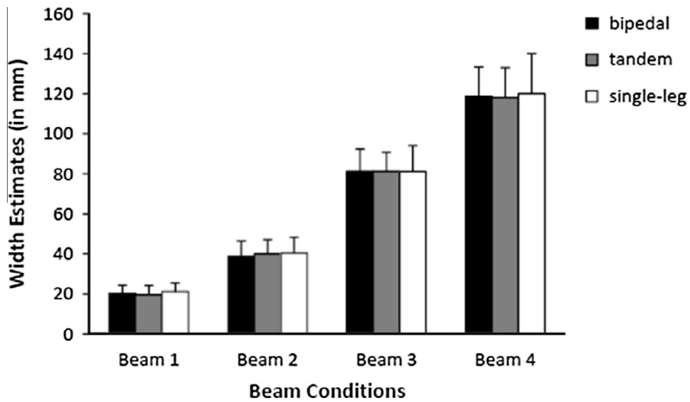

Fig. 3. Mean size estimates per beam (actual widths for beam 1 to beam 4: 17 mm, 36 mm, 84 mm and 135 mm) and stance condition. Bars indicate standard deviations (SD).

4. Discussion

Based on embodied theories of perception, it has been argued that perceptual estimates of action-relevant objects in the environment, such as the perceived width of a very narrow bridge one is about to walk over, may vary dependent on physiological (e.g., postural stability) and psychological states (e.g., arousal) (see e.g., Geuss et al., 2010; Proffitt, 2006; Proffitt & Linkenauger, 2013). In agreement with this idea, Geuss et al. (2010) showed that participants judged beams they imagined walking over to be narrower when they maintained an unstable body position than when maintaining a stable posture. Though Geuss et al. (2010) provided initial evidence that visual estimates of the environment are affected by postural stability, they did not measure the degree of postural sway to test their main hypothesis that as postural sway increases width estimates of action-relevant objects decrease. Therefore, in the current experiment we tested this hypothesis by asking participants to stand in three static, differently stable postures on a force plate measuring postural sway.

Importantly, and as demonstrated by our manipulation checks, the three stance conditions successfully changed postural stability and arousal in the predicted way. That is, participants showed significantly more postural sway in the single-leg stance than in the tandem stance, which again was characterized by significantly more postural sway than the bipedal stance. In addition, self-rated arousal scores also scaled with postural instability. It follows that the three different stances applied in our experiment changed postural stability and arousal as expected, thereby allowing us to test whether size estimates of the beams' widths decrease as body sway increases.

Our results do not confirm this hypothesis. They rather show that despite systematic differences in postural stability and levels of arousal, perceptual estimates of the beams' widths remained invariant. Fig. 3 clearly illustrates that for all four beam widths perceptual estimates were almost identical in the three stance conditions. We therefore conclude that perceptual estimates of the beams' widths remain invariant in the face of systematic variations to postural stability.

This finding is not in line with Experiment 1 of Geuss et al. (2010). We think that it is very unlikely that the different outcomes can be accounted for by methodological differences between their study and ours, perhaps with one exception. First, we used the same material: The length and widths of our beams were derived from and almost identical to those used in Geuss et al. (2010). Second, we adopted the same design. That is, we also applied a within-subjects design and presented each beam twice in each condition. Third, we had the same number of participants as Geuss et al. in their balance manipulation experiment. Fourth, we gave the same instructions. Fifth, we used the same arousal scale which yielded comparable results between our bipedal stance (i.e., our most stable and least arousing condition) and Geuss et al.'s low arousing IAPS manipulation as well as our tandem stance and Geuss et al.'s high arousing IAPS manipulation (see Geuss et al., 2010, Exp. 5A). Our single-leg stance even resulted in slightly higher arousal scores than reported by Geuss et al., thereby confirming that our manipulations had a similar impact on arousal. Sixth, their balance manipulation and ours were different in that we used three differently stable standing postures whereas they used two conditions, namely a stabilized and a rotating (i.e., unstable) balance board. It may be argued that our manipulation did not exceed a degree of postural sway and concomitant levels of arousal necessary to modulate perceptual estimates. Yet, we have good arguments to rule out this concern: If this were true, it would not make sense that even lower mean scores of arousal (4.86 in the high arousal condition reported in Geuss et al., 2010, Exp. 5A) than those observed in our single-leg condition (mean arousal score of 5.15) caused significant effects on perceptual estimates. In addition, Kerr et al. (1985) reported similar levels of postural sway (they also used the tandem stance) when compared to those we measured in the tandem and the single-leg stances. These levels of postural instability were sufficient to yield embodied effects of postural sway on spatial memory tasks. In addition, Geuss et al. (2010) did not quantify postural sway and hence did not provide an indication of how much sway would be sufficient to reproduce their findings. By contrast, we applied and quantified systematic changes to postural sway and hence feel on safe grounds to argue that perceptual estimates remained invariant despite the successful sway and arousal manipulations. If perceptual estimates were to be affected by postural sway, we should at least have observed a linear relationship between changes in postural sway (and arousal) and corresponding changes in perceptual estimates. However, as our analysis showed and Fig. 3 clearly illustrates, perceptual estimates remained stable in the face of variations in postural stability and arousal.

There is one final methodological difference that we can think of that may indeed be relevant in understanding the divergent results. For participants to provide width estimates of the beams, in Geuss et al. (2010) an experimenter held an outstretched tape measure and slowly decreased its length until participants told the experimenter to stop. This value was then noted and entered into the data file. Obviously, this method allows the experimenter to interfere with the dependent measure (i.e., the perceptual estimate). That is, the outcomes may – unwittingly – be influenced by experimenter bias (for similar methodological criticisms on demand characteristics and potential experimenter biases in research on embodied perception, see Durgin, Klein, Spiegel, Strawser, & Williams, 2012; Durgin, Baird, Greenburg, Russell, Shaughnessy, & Waymouth, 2009; Firestone, 2013; Shaffer, McManama, Swank, & Durgin, 2013; Woods, Philbeck, & Danoff, 2009). To nullify this concern in our study, participants provided their width estimates by drawing two vertical lines crossing a horizontal black line on a white sheet of paper; the distance between the two lines representing the width estimate of the beam. Hence, we feel that this methodological difference between Geuss et al. (2010) and our study, if anything, can only be interpreted in favor of the credibility of our findings.

We conclude that while our findings do not support the results and hypothesis put forward by Geuss et al. (2010), they contribute to a larger body of empirical and theoretical work questioning the robustness of some of the evidence brought up in favor of embodied views on perception (Firestone, 2013; Foerster, Gray, & Cañal-Bruland, 2015; Stins, Schulte-Fischedick, Meertens, & Cañal-Bruland, 2013), and hence enrich ongoing debates on this matter.

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