Multisensory Research

Joint Contributions of Auditory, Proprioceptive and Visual Cues on Human Balance

Max Teaford [1,2,3], Zachary J. Mularczyk [3], Alannah Gernon [3], Shauntelle Cannon [2], Megan Kobel [2] and Daniel M. Merfeld [2,3,*]

[1] Department of Psychology, The University of Tennessee at Chattanooga, Chattanooga, TN, USA

[2] Department of Otolaryngology, The Ohio State University Wexner Medical Center, Columbus, OH, USA

[3] Department of Acceleration and Sensory Sciences, Naval Medical Research Unit-Dayton, Wright Patterson Airforce Base, OH, USA

*Corresponding author: e-mail: merfeld.6@osu.edu

Supplementary material

S1. Supplemental Method

As noted in the manuscript, the conditions described in this manuscript were part of a larger study. Participants completed the following two additional conditions:

- Performing a dual task (i.e., counting backwards by 3s) while standing on a compliant surface while blindfolded.
- Standing on a memory foam surface while blindfolded.

S2. Supplemental Results

As noted in the manuscript, we also examined the impact of our manipulations on sway velocity and sway frequency Center of Pressure (CoP) parameters as well. Please see below for a detailed treatment of the results of these analyses.

S2.1 Contributions of Different Sensory Systems

S2.1.1 Sway Frequency

To examine the influence of visual (eyes open versus blindfold), auditory (ambient auditory cues not masked with broadband noise versus ambient auditory cues masked with broadband noise), and proprioceptive cues (firm surface versus compliant surface) on sway frequency values, a 2 × 2 × 2 repeated measures factorial ANOVA was performed. We found that there was a statistically significant main effect of:

- Vision, $F(1,16) = 16.46$, $p < .001$, $\eta_P^2 = .507$.
- Proprioceptive cues, $F(1,16) = 18.46$, $p < .001$, $\eta_P^2 = .536$.

However, there was not a main effect of:

- Auditory cues, $F(1,16) = 3.40$, $p = .084$, $\eta_P^2 = .175$.

There also was not an interaction between:

- Auditory cues and proprioceptive cues, $F(1,16) = 0.94$, $p = .347$, $\eta_P^2 = .055$.
- Auditory and visual cues, $F(1,16) = 0.00$, $p = .988$, $\eta_P^2 = .000$.
- Visual and proprioceptive cues, $F(1,16) = 0.04$, $p = .845$, $\eta_P^2 = .002$.
- Visual, auditory and proprioceptive cues, $F(1,16) = 1.21$, $p = .287$, $\eta_P^2 = .070$.

In order to better understand the main effects, condition means were examined. It was found that sway frequency was higher in the blindfold condition than in the eyes open condition. Additionally, sway frequency was higher on the compliant surface than on the firm surface. See Table 2 for the mean and SD of each condition.

S2.1.2 Sway Velocity

To examine the influence of visual (eyes open versus blindfolded), auditory (ambient auditory cues not masked with broadband noise versus ambient auditory cues masked with broadband noise), and proprioceptive cues (firm surface versus compliant surface) on sway velocity values, a 2 × 2 × 2 repeated measures factorial ANOVA was performed. We found that there was a statistically significant main effect of:

- Vision, $F(1,16) = 40.72$, $p < .001$, $\eta_P^2 = .718$.

- Proprioceptive cues, $F(1,16) = 113.85$, $p < .001$ $\eta_P^2 = .877$.

There was also an interaction between:

- Visual and proprioceptive cues, $F(1,16) = 84.91$, $p < .001$, $\eta_P^2 = .841$.

However, there was not a main effect of:

- Auditory cues, $F(1,16) = 1.45$, $p = .247$, $\eta_P^2 = .083$.

There also was not an interaction between:

- Auditory cues and visual cues, $F(1,16) = 0.55$, $p = .469$, $\eta_P^2 = .033$.
- Auditory and proprioceptive cues, $F(1,16) = 1.45$, $p = .247$, $\eta_P^2 = .083$.
- Visual, auditory and proprioceptive cues, $F(1,16) = 0.03$, $p = .870$, $\eta_P^2 = .002$.

Post hoc Bonferroni tests were utilized to characterize the interaction between the visual and proprioceptive cues. It was found that Sway Velocity values were higher in the blindfold condition than the eyes open condition (both p values < .01). This difference was more pronounced while standing on the compliant surface (p <.001). In other words, while blindfolded participants swayed faster than when not blindfolded. This difference was larger when standing on the compliant surface than when standing on the firm surface. See Table 2 for the mean and SD of each condition and Supplementary Fig. S1 for a graph depicting the interaction.

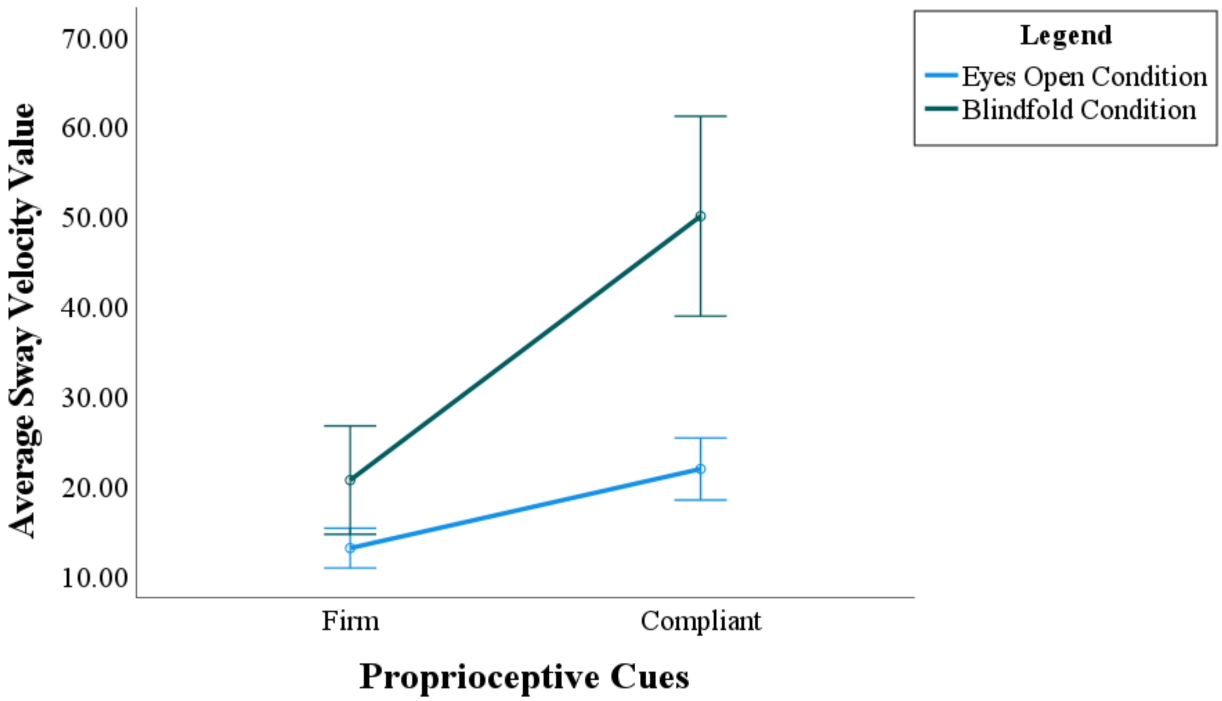

Figure S1.

A profile plot depicting the interaction between the support surfaces and visual conditions when comparing sway velocity values. Note the error bars are based upon the 95% CI.

Table S1.
The mean and SD for each condition for each of our CoP metrics.

	Sway Frequency Mean (SD)	Sway Velocity Mean (SD)
Eyes Open (i.e., Real World)- No Auditory Masking – Firm Surface	0.34 (0.12)	12.76 (4.28)
Blindfold – No Auditory Masking – Firm Surface	0.47 (0.19)	19.74 (10.53)
Eyes Open (i.e., Real World)- No Auditory Masking – Compliant Surface	0.48 (0.14)	23.94 (9.58)
Blindfold - No Auditory Masking – Compliant Surface	0.57 (0.19)	49.98 (22.88)
Virtual Visual- No Auditory Masking – Firm Surface	0.43 (0.14)	16.52 (7.14)
Virtual Visual- No Auditory Masking – Compliant Surface	0.58 (0.26)	44.02 (41.45)
Eyes Open (i.e., Real World)- Auditory Masking – Firm Surface	0.40 (0.12)	13.44 (4.68)
Blindfold – Auditory Masking – Firm Surface	0.50 (0.21)	21.58 (13.92)
Eyes Open (i.e., Real World)- Auditory Masking – Compliant Surface	0.49 (0.15)	23.72 (10.27)
Blindfold – Auditory Masking – Compliant Surface	0.59 (0.19)	50.09 (20.80)
Virtual Visual- Auditory Masking - Firm Surface	0.46 (0.21)	16.41 (6.91)
Virtual Visual- Auditory Masking - Compliant Surface	0.61 (0.28)	43.64 (37.72)

Note: “No Auditory Masking” is short for no ambient auditory cue masking with broadband noise and “Auditory Masking” is short for “ambient auditory cue masking with broadband noise.

S2.2 Virtual vs. Real World Visual Cues

S2.2.1 Sway Frequency

To determine if the masking of auditory cues (ambient auditory cues not masked with broadband noise versus ambient auditory cues masked with broadband noise), the use of virtual reality (virtual versus real world visual cues), and the proprioceptive cues (firm surface versus compliant surface) impacted Sway Frequency, a 2 × 2 × 2 repeated measures factorial ANOVA was performed. We found that there was a statistically significant main effect of:

- VR visual cues, $F(1,16) = 8.77$, $p = .009$, $\eta_P^2 = .354$.
- Proprioceptive cues, $F(1,16) = 17.50$, $p < .001$, $\eta_P^2 = .522$.

However, there was not a statistically significant main effect of :

- Auditory cues, $F(1,16) = 3.61$, $p = .076$, $\eta_P^2 = .184$.

It was also found that there was not a statistically significant interaction between:

- VR visual cues and auditory cues, $F(1,16) = 0.50$, $p = .826$, $\eta_P^2 = .003$.
- Proprioceptive cues and auditory cues, $F(1,16) = 2.06$, $p = .170$, $\eta_P^2 = .114$.
- VR visual cues and the proprioceptive cues, $F(1,16) = 1.76$, $p = .204$, $\eta_P^2 = .099$.
- Auditory cues, VR visual cues, and proprioceptive cues, $F(1,16) = 1.52$, $p = .236$, $\eta_P^2 = .087$.

The condition mean values were utilized to better understand the main effects reported above. It was found that sway frequency values were higher in the virtual visual condition than in the real world visual condition. Additionally, sway frequency values were higher on the compliant surface than on the firm surface. See Table S1 for the mean and SD of each condition.

S2.2.2 Sway velocity

To determine if the masking of auditory cues (ambient auditory cues not masked with broadband noise versus ambient auditory cues masked with broadband noise), the use of virtual reality (virtual versus real world visual cues), and the proprioceptive cues (firm surface versus compliant surface) impacted the sway velocity a 2 × 2 × 2 repeated measures factorial ANOVA was performed. We found that there was a statistically significant main effect of:

- VR visual cues, $F(1,16) = 8.91$, $p = .009$, $\eta_P^2 = .358$.
- Proprioceptive cues, $F(1,16) = 11.96$, $p = .003$, $\eta_P^2 = .428$.

There was also a statistically significant interaction between:

- Proprioceptive cues and VR visual cues, $F(1,16) = 5.44$, $p = .033$, $\eta_P^2 = .254$.

However, there was not a statistically significant main effect of:

- Auditory cues, $F(1,16) = 0.00$, $p = .990$, $\eta_P^2 = .000$.

It was also found that there was not an interaction between:

- VR visual cues and auditory cues, $F(1,16) = 0.12$, $p = .730$, $\eta_P^2 = .008$.
- Proprioceptive cues and auditory cues, $F(1,16) = 0.20$, $p = .658$, $\eta_P^2 = .013$.
- Auditory cues, VR visual cues and proprioceptive cues, $F(1,16) = 0.035$, $p = .854$, $\eta_P^2 = .002$.

In order to better understand the interaction between VR visual cues and proprioceptive cues, we utilized post hoc Bonferroni Tests. It was found that the sway velocity values were higher in the VR visual condition than in the real visual world condition regardless of surface (both p-values $< .05$). However, the difference was more pronounced when the participants were standing on the compliant surface ($p < .05$) See Table 2 for the mean and SD of each condition and Supplementary Fig. S2 for a graph depicting the interaction.

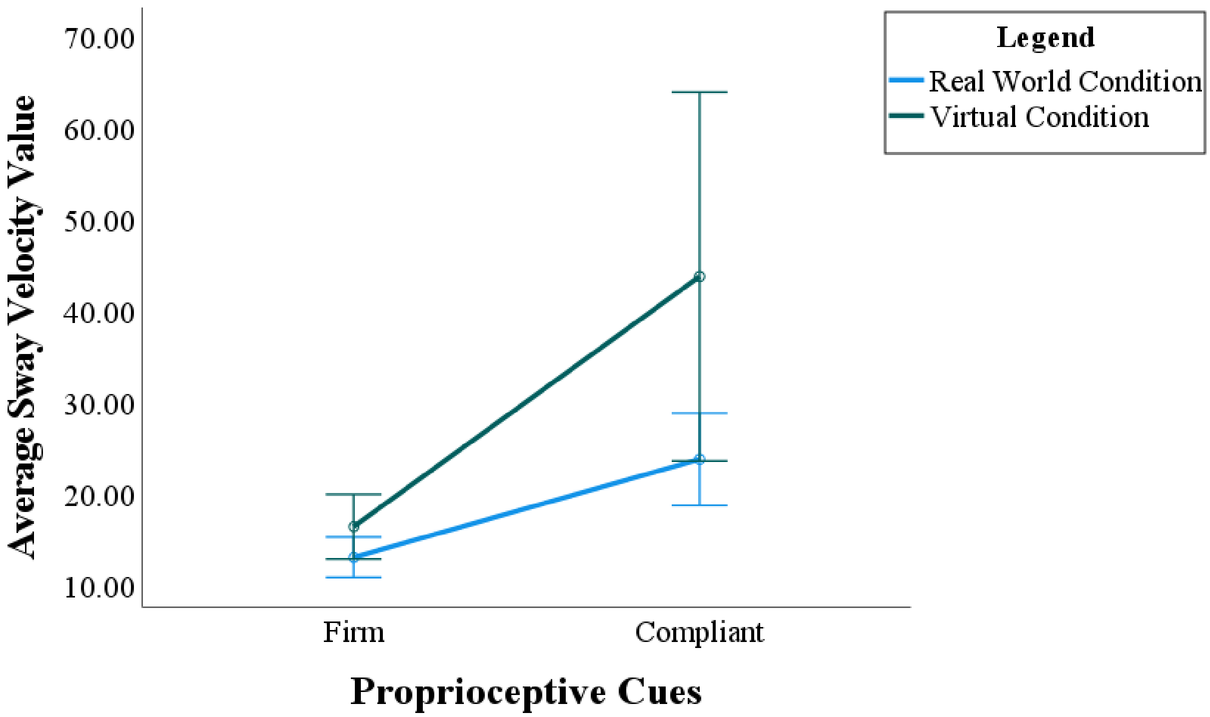

Figure S2.

A profile plot depicting the interaction between proprioceptive cues and the virtual/real world conditions when comparing sway velocity values. Note the error bars are based upon the 95% CI. Additionally, "Real World Condition" is short for real world visual condition and "Virtual Condition" is short for virtual visual condition.