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Journal Qualification

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VISUAL REWEIGHTING USING STROBOSCOPIC VISION IN HEALTHY INDIVIDUALS

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Jang et al., Testing how individuals use visual information to maintain balance has been traditionally limited to two extreme conditions: eyes closed and eyes open. Stroboscopic glasses allow clinicians to control the amount of visual information that influences balance, varying between eyes open and closed. Seventeen uninjured participants completed the sensory organization test (SOT) under three visual conditions: full occlusion, high occlusion (i.e., 100ms transparent, 400ms opaque), and low occlusion (i.e., 100ms transparent, 100ms opaque). Equilibrium scores were calculated from the Neurocom Balance Master system during double-limb stance and the three-trial average from each condition and SOT was used for analysis. A two-way repeated measures ANOVA was used to evaluate the interaction between and within factors of vision (i.e., full occlusion, high occlusion, low occlusion, and no occlusion) and support surface (i.e., firm and sway). Increased visual occlusion negatively impacts balance on a firm surface and is amplified when somatosensory cues are unreliable. These findings highlight the importance of somatosensory cues as a guiding sensory modality for balance, especially when vision is occluded.

Key Words: sensory organization test, balance, Neurocom Balance Master

Introduction

How do we maintain our balance when our eyes are closed or are in a challenging environment? Sensory modalities such as the visual, somatosensory, and vestibular systems play a crucial role in continuously refining our balance (Jacobs & Horak, 2007). One goal of the central nervous system (CNS) is to determine the most accurate and reliable source of sensory information required to maintain balance (Horak, 2006). The shifting of the relative contributions (i.e., weight) among sensory modalities is known as sensory reweighting (Assländer & Peterka, 2014; Nashner & Berthoz, 1978; Peterka, 2002). Sensory reweighting is necessary to maintain balance in a variety of environments and conditions, especially when information from one sense produces inaccurate information (Peterka & Black,

1990; Prieto et al., 1993). For example, standing on an unstable surface alters the frame of reference for somatosensory signals which likely leads to an upregulation of visual and vestibular feedback. However, such sensory reweighting often results in a trade-off to balance performance, which is a common observation, especially when comparing eyes-open and eyes-closed balance. Closing the eyes or eliminating the source of visual information supplied to the CNS results in worsened balance (Berthoz et al., 1979; Lee & Lishman, 1975; Redfern et al., 2001), which may be attributed to inefficient reweighting towards other sensory systems to compensate in the absence of visual input (Assländer & Peterka, 2014).

Vision provides appropriate stabilizing cues to the brain when we encounter challenging balance conditions (Day et al., 1993). Some patients with

musculoskeletal injuries are known to exhibit aberrant reweighting patterns (i.e., increased reliance on vision) during balance (Grooms et al., 2015, Song et al., 2016). Quantifying these reweighting trade-offs among sensory modalities can be accomplished using testing protocols designed to limit or manipulate the fidelity of each sense. The sensory organization test (SOT) was developed to manipulate visual and somatosensory inputs and calculate sensory reweighting scores based on balance performance. Stroboscopic glasses such as Senaptec Strobe (Senaptec LLC., Beaverton, OR, USA) can be used to further stress visual processing (Grooms et al., 2015; Kim et al., 2017; Kim et al., 2020). For example, Grooms et al. suggested that incorporating SV with traditional neuromuscular intervention can target the CNS after an anterior cruciate ligament injury (Grooms et al., 2015). Single-limb balance in uninjured adults using SV was worse than eyes open but better than the eyes-closed balance when participants balanced on a firm surface (Kim et al., 2017). Yet, when the reliability of somatosensory cues was reduced by standing on a foam surface, SV balance and eyes-closed balance were significantly worse than eyes-open balance (Kim et al., 2017). Similarly, uninjured individuals exhibit higher reliance on vision when somatosensory inputs were disturbed during single leg balance (Lee et al., 2022). This follows the idea that balance degrades further when multiple sensory modalities are disrupted or become unreliable.

To date, little attention has been placed on how balance is maintained when vision is occluded. This restricts our understanding of how our brain reweights towards other sensory modalities as the amount of visual input is manipulated. Some patients with musculoskeletal injuries (e.g., chronic ankle instability (Song et al., 2016), chronic low back pain (Claeys et al., 2011), or anterior cruciate ligament deficiency (Wikstrom et al., 2017)) show an increased reliance on visual cues during movement and have poor postural control. It is possible individuals would rely more on visual feedback for postural control as more rapid and direct feedback (i.e., somatosensation) is degraded as a result of injury and/or aging processes (Nashner & Berthoz, 1978; Speers et al., 2002). Considering the link between visual feedback and motor output, it is possible that

altered sensory organization may contribute to recurrent injuries. It is therefore critical to examine novel protocols that can assess sensory reweighting under different levels of visual disruption. By combining the SOT and SV, we can probe the intricacies of visual reweighting that occur between the two extremes of eyes-open and eyes-closed balance. Therefore, the purpose of this study was to examine the interaction between varying levels of visual occlusion and support surface stability. We hypothesized that balance would be worse as visual occlusion increased, and this would be further amplified when combined with somatosensory feedback was manipulated.

Methods

Participants

A total of 17 young adults (8 males, age: 26.0 ± 3.9 years, BMI: 23.01 ± 1.86 and 9 females, age: 23.3 ± 4.1 years, BMI: 24.69 ± 3.02) were recruited from a large public university in this study. Pilot testing on four participants revealed a range of Hedges' g effect sizes from 0.45 to 1.19. A within-factors repeated measures power analysis using the smallest effect size (ES: 0.45, β = 0.80, α = 0.05) indicated that 15 participants would be required for this investigation. None of our participants self-reported wearing corrective glasses or lenses. Individuals were included if they were between 19-35 years old and had self-reported leisure physical activity levels greater than 90 total minutes per week. Participants were excluded if they had a history of any injuries to their lower extremities that disrupted their physical activity or required formal rehabilitation. Participants with a history of neurological disorders such as a concussion or vestibular weakness, family history of epilepsy, history of diabetes, as well as a history of severe migraines were excluded. Prior to participation in the study all participants provided written informed consent. The study protocol was approved by the local university IRB committee.

Experimental Procedure and Equipment

In brief, participants completed 3 complete versions of the SOT, one without any visual occlusion, one with low visual occlusion, and one with high visual occlusion. We used Senaptec Strobe goggles (Senaptec, Beaverton, OR) to occlude vision with a
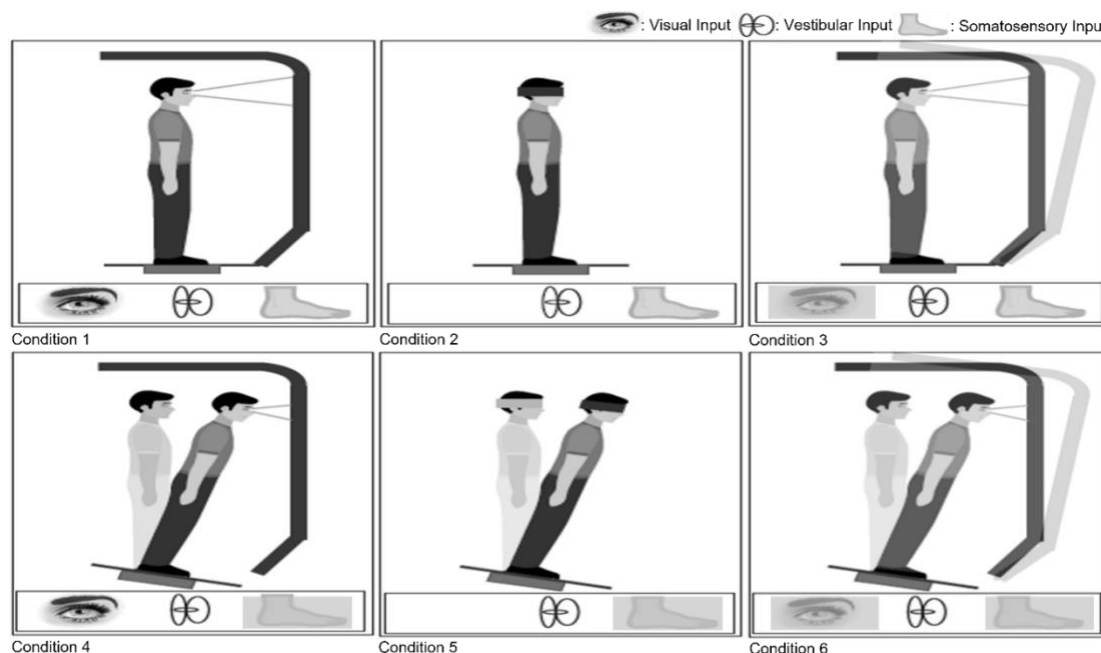
stroboscopic effect. These goggles switch between opaque and transparent lenses at set intervals. To test the effects of progressive visual occlusion on sensory reweighting, we used four different levels of vision (i.e., no occlusion, high occlusion SV, low occlusion SV, and eyes closed). The first three levels of vision were measured in condition 1 (i.e., firm support) and 4 (i.e., sway-referenced support). The eye closed vision was measured in condition 2 (i.e., firm support) and 4 (i.e., sway-referenced support). The low occlusion was equivalent to an individual blinking five times per second, where it has 100ms intervals of opacity and transparency for each cycle. This level was used in order to provide comparisons with previously published research on standing balance and drop-landings (Grooms et al., 2015; Kim et al., 2017). High visual occlusion was selected as it represented dynamic sensory reweighting ~2 Hz with 400ms interval of opacity and a 100ms interval of transparency for each cycle. Participants were wearing SV goggles during the entire testing period and were set to transparent during eyes open trials. Prior to testing, participants had a familiarization session with SV for 5 minutes. The 5 minutes approximated the time it takes to complete 1/6th of

the testing protocol. The 5 minutes were split into two periods: 1) walking around the indoor track in the 1st period of 2.5 minutes in high occlusion SV and 2) the 2nd period of another 2.5 minutes in low occlusion SV. All participants completed the familiarization period without any concerns or issues.

The SOT is a testing protocol that measures balance while one or more sensory modality is manipulated (Chaudhry et al., 2004). The SOT conditions were: eyes open without altered sensory stimuli (condition 1, C1); eyes closed without altered sensory stimuli (condition 2, C2); eyes open with altered visual stimuli via a moving wall according to the participant's anterior/posterior sway (i.e. sway-referenced vision), thus maintaining the visual distance at all time between their eyes and the wall (condition 3); eyes open with altered proprioceptive stimuli via a moving platform according to the participant's anterior/posterior sway (i.e. sway-referenced platform), thus maintaining their ankle joint angle at all times (condition 4, C4); eyes closed with the sway-referenced platform (condition 5, C5); eyes open with the sway-referenced vision and platform (condition 6). A representation of the SOT protocol can be found in Figure 1.

Figure 1

Sensory Organization Test. Gray shaded area indicates perturbation of the corresponding sensory input (Natus Medical, 2016).

Participants completed three randomly ordered SOTs consisting of high-, low-, and no- occlusion protocols. For example, one could do high-, low-, and no- occlusion SOTs in order, whereas another could do low-, high-, no- occlusion in order depending on randomization. More specifically, goggles were set to high occlusion at all time throughout the high occlusion SOT. Goggles were set to transparent throughout the no occlusion SOT. Eyes remained closed during condition 2 and 5 of each SOT and only condition 2 and 5 in the first SOT were used for analyses to avoid any potential learning effects from the same trials in the second and third SOTs. The SOT consists of three, 20-seconds trials for each of the 6 SOT conditions. Participants completed a total of eighteen trials within each SOT. Three trials for each condition were averaged. Moreover, within each SOT, the order of six conditions was also randomized every time via random number functions in Microsoft Excel (Microsoft Corp, Redmond, WA) to minimize any learning effect or adaptation to the sensory manipulations. Therefore, a total of 54 trials (i.e. 3 SOTs × 6 conditions × 3 trials) were conducted for each individual. Participants took a 1-minute seated break after every nine trials. A total testing time for each participant took 1,380 seconds (i.e., 54 trials × 20 seconds + 5 breaks sessions × 60 seconds). All Participants were harnessed to ensure their safety throughout the testing protocol. Participants were asked to maintain balance as best as they could during testing.

Outcome Measures and Analysis

The NeuroCom Balance Manager Systems calculates equilibrium scores for each trial in each condition according to equation (1):

Equilibrium scores= {12.5 - [θ_max (ant)-θ_max (post)]} ⋁ 12.5, where θ_{max} (ant) is the maximum anterior sway angle in degrees during each trial, θ_{max} (post) is the maximum posterior sway angle in degrees during the trial, 12.5 is the limit of sway in degrees in the sagittal plane for a normal stance and a constant number of 12.5° is assumed to be the limit angle of stability for an average individual (Natus Medical, 2016). Higher scores in equilibrium scores indicate a better balance. The three-trial average

equilibrium score for each 20-second trial for each condition was used for analysis in this study.

Statistics

A two-way repeated measures ANOVA with a Greenhouse-Geisser correction was conducted to evaluate the interaction and main effects of visual occlusion (4 levels: full- [C1/C4], high-[C1/C4], low-[C1/C4], no occlusion[C2/C5]), support (2 levels: firm and sway-referenced), and the SOT conditions. Hedges' g effect sizes and 95% confidence intervals were calculated across condition 1 with 3 levels of visual occlusion (high, low, and no occlusion) and condition 2 (full occlusion), and condition 4 with 3 levels of visual occlusion and condition 5 to investigate the systematic effects of visual occlusion with and without perturbations of somatosensory input. Conditions 3 and 6 were not used for analysis, however, performance in these conditions can be seen in Figure 3. For condition 2 and 5 where there is no visual input (i.e., closing eyes), equilibrium scores of the first SOT the participant completed were used for comparisons. Effect sizes were interpreted as small with 0.2, medium with 0.5, and large with 0.8 values (Hedges, 1981). SPSS statistical software package v.24.0 (SPSS, Inc., Chicago, IL, USA) was used for all analyses, where $p < .05$ was considered statistically significant.

Results

A two-way repeated ANOVA was run to determine the effect of different amounts of visual occlusion as well as different support on the SOT conditions. Mauchly's test of sphericity indicated that the assumption of sphericity had been violated for the two-way interaction, $\chi2(54) = 153.19$, $p < .001$. A significant interaction between visual occlusion and conditions on equilibrium scores was observed, $F(3.480, 55.679) = 3.453$, p = .018, partial η2 = .178. Therefore, simple main effects were run (Keppel & Wickens, 2004). Mean equilibrium scores were significantly different over three types of vision in condition 4, $F(2, 32) = 10.665$, $p < .001$. Post hoc analysis with a Bonferroni adjustment revealed that equilibrium scores were significantly decreased from no occlusion to high occlusion (10.035(95% CI, 2.509 to 17.561) and from low occlusion to high occlusion

(5.882(95% CI, 1.277 to 9.887). Mean equilibrium scores were significantly different over 6 types of condition during no occlusion, $F(5, 80) = 44.552$, $p < .001$; low occlusion, $F(5, 80) = 37.911$, p < .001; high occlusion, $F(5, 80) = 34.640$, $p < .001$. Post hoc analysis with a Bonferroni adjustment of simple main effect for conditions can be found in the supplement data. Effect sizes and 95% confidence intervals can be found in Figure 2.

Figure 2

Hedges'g effect sizes and 95% confidence intervals. The Forest plot of pairwise comparisons is represented as Mean ± SD (right). Condition 1: eyes open (i.e., no-, high- , low- occlusion stroboscopic vision), stable support, Condition 2: eyes closed, stable support, Condition 4: eyes open (i.e., no-, high- , low- occlusion stroboscopic vision), sway-referenced support, Condition 5: eyes closed, sway-referenced support.

	Effect Size and 95% Confidence Interval
condition 1 no occlusion vs condition 1 low occlusion	0.42±0.68
condition 1 no occlusion vs condition 1 high occlusion	0.24±0.67
condition 1 no occlusion vs condition 2	1.21±0.73
condition 1 low occlusion vs condition 1 high occlusion	-0.07±0.67
condition 1 low occlusion vs condition 2	1.18±0.73
condition 1 high occlusion vs condition 2	0.95±0.71
condition 4 no occlusion vs condition 4 low occlusion	0.53±0.69
condition 4 no occlusion vs condition 4 high occlusion	0.83±0.7
condition 4 no occlusion vs condition 5	1.59±0.78
condition 4 low occlusion vs condition 4 high occlusion	0.85±0.7
condition 4 low occlusion vs condition 5	0.81±0.71
condition 4 high occlusion vs condition 5	0.33±0.68

Discussion

This study aimed to investigate the trade-offs in balance performance between visual and somatosensory perturbations. Both types of sensory information are critical for balance under normal conditions, but there may be situations where these senses provide less detailed information about the environment to the CNS (e.g., running on a beach, hiking in low light, after injury). Our findings indicate that balance is worsened as vision is progressively occluded and when the somatosensory input is disrupted. One strength of the SOT protocol is it allows one to observe the trade-offs that occur because of sensory reweighting when other senses are blocked or manipulated. Our design probed this relationship further by using two additional levels of visual occlusion: high- and low-occluded SV. The SV occluded vision by limiting the amount of time the visual system could sample the environment as they transition between transparent and opaque states. Our data support that balance in healthy adults was not significantly affected by any level of SV when they were standing on firm support. However, as expected we observed steep declines in equilibrium scores were observed when they were standing on sway-referenced support with occluded vision.
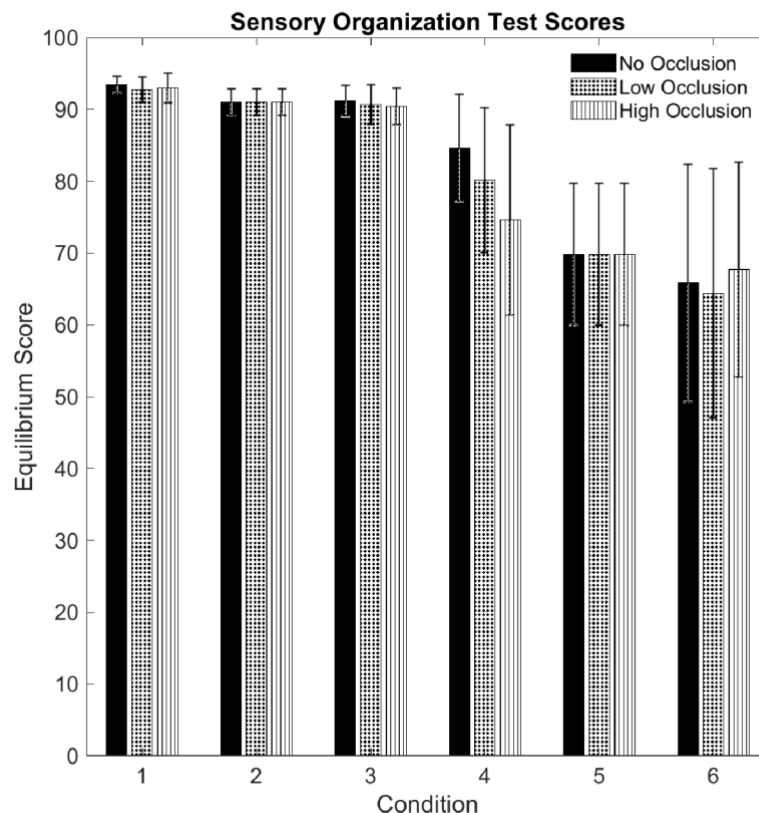
The decline in balance performance under combined visual and somatosensory disruption indicates that occluding vision with SV likely reweights sensory modalities in a manner that upregulates the use of somatosensory cues. It is common knowledge that balance is worsened when the eyes are closed; indeed, our data showed a significantly worsened balance between condition 1 and condition 2. Moreover, the equilibrium scores in condition 1 with 3 levels of visual occlusion (high, low, and no occlusion) were significantly different from condition 2 (full occlusion) (Figure 2). Our results help reaffirm the importance of having continuous visual

and somatosensory cues for optimal balance output. Both progressive visual occlusion and support surface manipulations degraded balance performance, as expected (Figure 3), however previous studies have not looked at various levels of visual occlusion as we did in our investigation. The exact percentages of weight of each sensory modality are still not known for ideal conditions (i.e., eyes-open on a stable surface in a well-lit environment), however, modeling studies have provided good estimates. Peterka (2002) suggests that the relative weight of visual and somatosensory information to standing balance is approximately 10% and 70%, respectively (Peterka, 2002). We feel our data partially supports these findings as our participants achieved a good equilibrium score across condition 1 with 3 levels of visual occlusion and condition 2 (i.e., eyes closed) where they have unperturbed somatosensory input (i.e., ~70% of weight) despite of systematic visual occlusion (i.e., ~10% of weight), yet the differences were very small in magnitude (Figure 3).

Figure 3

Sensory Organization Test – Equilibrium score results of no-, low-, and high- occlusion. For conditions 2 and 5, equilibrium scores from the first measured SOT were only used for comparisons. Thus, the same scores (i.e., mean and SD) were noted in conditions 2 and 5. Higher equilibrium scores indicate better balance, and lower scores indicate worsened balance. Condition 1: eyes open (i.e. no-, high-, low- occlusion stroboscopic vision), stable support, Condition 2: eyes closed, stable support, Condition 3: sway-referenced vision (i.e. no-, high-, low- occlusion stroboscopic vision), stable support, Condition 4: eyes open (i.e. no-, high-, low- occlusion stroboscopic vision), sway-referenced support, Condition 5: eyes closed, sway-referenced support, Condition 6: eyes open, sway-referenced vision (i.e. no-, high-, low- occlusion stroboscopic vision), and sway-referenced support.

More specifically, different amounts of visual cues due to SV did not significantly affect one's standing balance as vision takes only 10% of weight whereas somatosensory cues take about 70% of weight according to Peterka (2002). The suggested sensory weights by Peterka (2002) are based on ideal conditions only, and our condition 4 and condition 5 indicate that these weights may be drastically shifted based on environmental constraints/demands (e.g., sway-referenced balance). During condition 4 and condition 5 our uninjured young participants likely placed less weight on somatosensory signals and upregulated visual cues as a result. It is difficult to speculate on vestibular contributions to balance as no condition directly perturbed or manipulated vestibular input. Future research is warranted to further investigate how a healthy sensorimotor system reweights contributions using more direct measures of CNS function.

Our results share some similarities with the existing SV literature as both studies used 100ms intervals of opacity and transparency for each cycle (i.e., low occlusion). Both studies were able to show that balance was significantly worsened with the eyes-closed when somatosensory information was less reliable (Kim et al., 2017). In our study somatosensory information was perturbed using platform rotations whereas Kim et al. used a foam pad to dampen somatosensory cues. During the SOT the support surface has the same density as the unperturbed somatosensory conditions, however it rotates about a fixed axis for the anterior-posterior displacements of the center of pressure (COP) during condition 4 and condition 5. This manipulation likely forces the CNS to constantly re-identify a frame of reference for utilizing plantar somatosensory cues during sway-referenced balance conditions. We speculate that foam pads and compliant surfaces could lead to a situation where the time it takes the CNS to detect displacements is increased due to the physical properties of the surface. Thus, in theory, we would likely observe a reweighting away from this sensory modality when maintaining balance. The exact neurophysiological mechanisms of sensory processing and reweighting in both of these conditions/surfaces have not yet been investigated. Regardless of the underlying mechanism, either

method of manipulating somatosensory cues seems to be effective in forcing sensory reweighting. In comparison to Kim et al, our study further investigates this effect by adding one additional condition (i.e., high occlusion) in between low occlusion and full occlusion. Interestingly, a large effect was noted when no occlusion and high occlusion were compared (g: 0.83). Further, the fact that a large effect was found between low occlusion and high occlusion (g: 0.85) indicates that the high occlusion can be utilized in rehabilitation as the intermediate level between low occlusion and full occlusion. This intermediate level of visual condition can be utilized to create a more specific rehabilitation by providing a medium level of condition between two extremes. Indeed, a recent study comparing the effects of different levels of SV in rehabilitation in patients with CAI (i.e., higher reliance on visual cues) revealed better outcomes in both static and dynamic balance than those without SV (Lee et al., 2022). No participants in our investigation lost their balance completely, fell, or scored so poorly on a trial that they had an equilibrium score of 0. None of our participants completely lost their balance under any constrained sensory conditions during testing. This is likely due to proper reweighting of sensory inputs as we sampled young adults without a history of injury. Future studies could use a similar protocol to investigate age-related or injury-related insufficiencies in sensory reweighting.

Our findings also differ from the previous work on SV during single limb balance (Kim et al., 2017). Figures 2 and 3 show an intricate relationship of trade-offs that occur as visual cues are modulated and the support surface is manipulated. However, no differences were observed in equilibrium scores where we had expected: our initial hypotheses led us to anticipate that balance performance during SV would be worse relative to eyes-open balance on the firm support, consistent with Kim et al (2017). Our results contradict previous findings of worsened single-limb balance during SV (at a rate equivalent to our low occlusion) relative to eyes-open (Kim et al., 2017). Our results indicate that the complete removal of visual cues (i.e., full occlusion) resulted in worse double-limb balance than any amount of vision, regardless of SV. Further, there were no differences

between SV frequencies. On the contrary to the results of foam support in Kim et al., our results indicate no significant differences between eyes open and low occlusion on the sway-referenced support (i.e., conditions 4 and 5). However, we observed that balance was worse during high, relative to low, occlusion. This could be attributed to the difficulties and demands of the balance task in both studies. Static balance is related to areas of base of support of an object (Hall, 2006; Horak, 2006; Pollock et al., 2000) and decreased base of support increases COP displacements in healthy young adults (Albertsen et al., 2017). The reduced base of support has been reported to increase COP excursions and velocity (Black et al., 1982). Thus, a broader base of support from a double-limb stance in our study might cause different results from their research where participants were in single-limb balance, which is assumed to be more challenging.

One limitation of our study is that the equilibrium scores are calculated based on anterior and posterior displacements of the COP. It is possible we may have under-estimated the effect of SV and sway-referenced balance, as our primary outcome measure fails to account for medial-lateral movements. However, a consequence of this limitation is that our findings can serve as the minimum-expected differences due to SV and sensory reweighting during standing balance. Secondly, we could not control the actual blinking frequency of our participants. Although SV duty cycles were set at a controlled rate, it is still possible that a participant could blink during any given transparent phase. We did not track eye movement or blink rate, so it is possible this may have introduced some additional difficulty into the conditions with SV, being used to generate inferences on central processes of sensory modality reweighting. Third, all of our participants were recruited throughout university settings, meaning that our findings cannot be generalized to the general population or patient populations who are most likely to use the SOT. Fourth, SV goggles may not be accessible to some clinicians or researchers, which makes it difficult to utilize our findings. Finally, we did not measure participants' fatigue levels during the testing. However, none reported any fatigue or dizziness as they were young and healthy and went through the familiarization session before testing without any issues.

Conclusion

This study reaffirms the importance of the CNS using multiple senses for maintaining balance. We found that balance worsened as the vision was progressively occluded and this effect was magnified when somatosensory input from the feet was compromised. This shows the importance of somatosensation (e.g., touch, pressure, or movement on the plantar aspect of the foot) as a guiding sensory modality for balance, especially when visual conditions are limited. Moreover, SV may effectively manipulate our visual sampling rate and reduce the amount of visual information individuals obtain. Thus, SV can be utilized to investigate the intricacies of visual reweighting that occur between two extremes of eyes-open and eyes-closed balance. This may be useful for a more in-depth assessment of sensorimotor function in populations with poor balance such as those with chronic musculoskeletal injuries or the elderly.

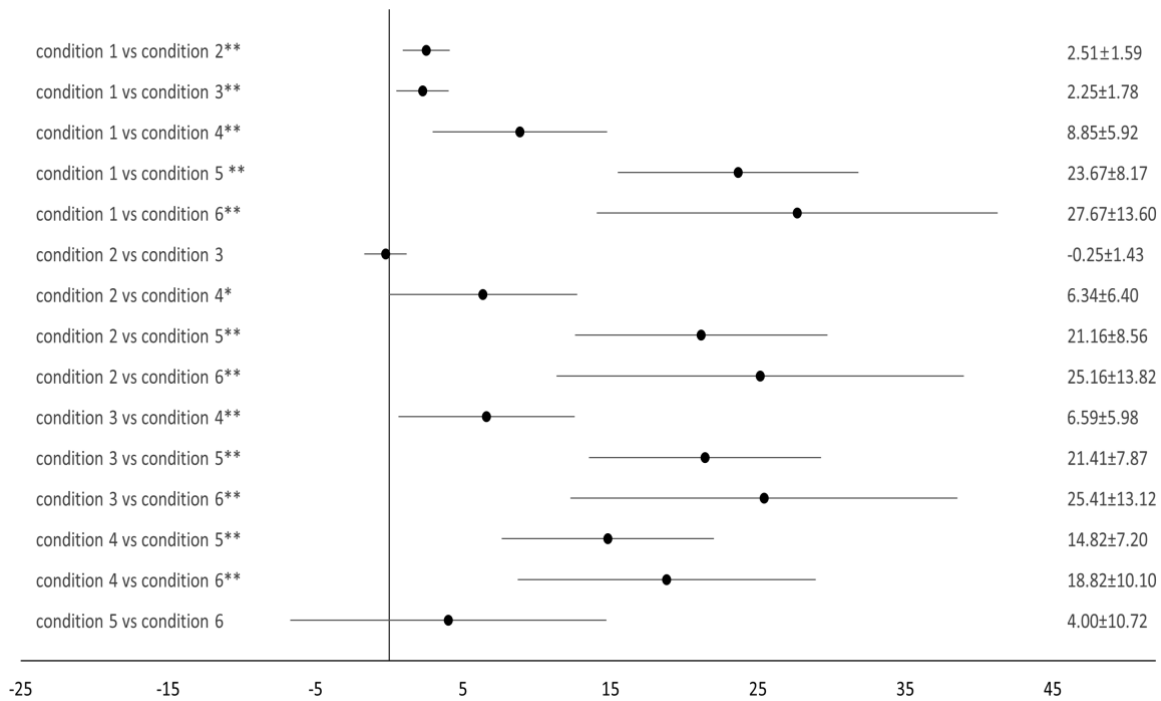### References

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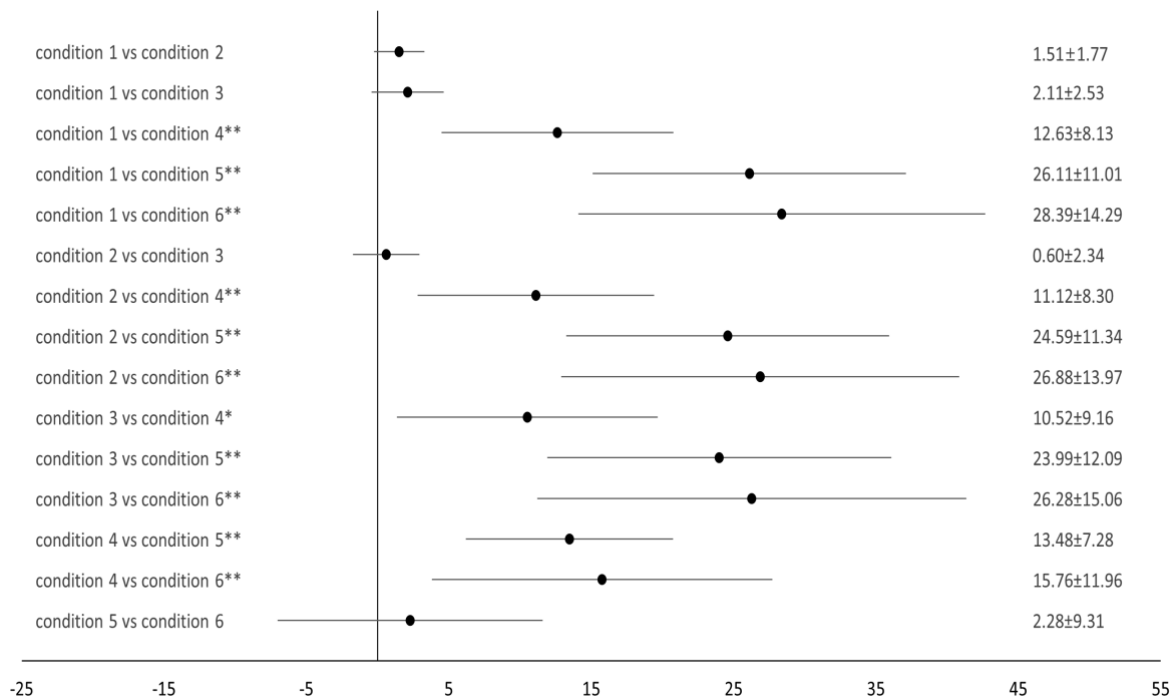
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Supplements

Supplement 1-a. Mean differences of equilibrium scores across conditions during no occlusion. Forest plot of pairwise comparisons is represented as Mean±SD (right). *: p<.05 and **: p<.01.

condition 1 vs condition 2		1.51±1.77
condition 1 vs condition 3		2.11±2.53
condition 1 vs condition 4**		12.63±8.13
condition 1 vs condition 5**		26.11±11.01
condition 1 vs condition 6**		28.39±14.29
condition 2 vs condition 3		0.60±2.34
condition 2 vs condition 4**		11.12±8.30
condition 2 vs condition 5**		24.59±11.34
condition 2 vs condition 6**		26.88±13.97
condition 3 vs condition 4*		10.52±9.16
condition 3 vs condition 5**		23.99±12.09
condition 3 vs condition 6**		26.28±15.06
condition 4 vs condition 5**		13.48±7.28
condition 4 vs condition 6**		15.76±11.96
condition 5 vs condition 6		2.28±9.31

Supplement 1-b. Mean differences of equilibrium scores across conditions during low occlusion. Forest plot of pairwise comparisons is represented as Mean±SD (right). *: $p < .05$ and **: $p < .01$.

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