

Potential Effects of Sleep Deprivation on Sensorimotor Integration during Quiet Stance in Young Adults

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Abstract

The purpose of this study was to compare the effects of sleep deprivation and rest on postural control. It was hypothesized that significant increases in COP deviations will occur after sleep deprivation. *Methods.* Four healthy adults (age= 21.50 years; mass= 68.93 kg) participated in two protocols involving sleep and sleep-deprivation. Within each condition multiple 40s impairments of visual, somatosensory, and/or vestibular sensory feedback were performed. Balance was quantified using root-mean-square (RMS) of the centre of pressure (COP) and COP Variance. *Results.* Two-way ANOVA demonstrated no significant effect of sleep deprivation on balance between sensory insults. Paired t-tests were performed nonetheless and revealed significant differences within the sleep-deprived condition. COP RMS and Variance were significantly greater medio-laterally with all systems impaired (ALL) (3.43 ± 0.63 mm, $p < 0.05$; and 4.6 ± 1.60 mm, $p < 0.05$) than with all systems unimpaired (QS) (2.36 ± 0.24 and 2.1 ± 0.45). Also, COP RMS was significantly greater in the visual/vestibular-impairment condition (3.19 ± 0.63 , $p < 0.05$) than in QS. Antero-posteriorly, COP RMS and Variances were significantly greater in ALL (7.0 ± 9.40 , $p < 0.05$; 20.30 ± 9.39 , $p < 0.05$), compared to QS (4.39 ± 1.01 and 6.64 ± 2.73). These values were both significantly greater than measurements in visual-impairment (RMS= 4.43 ± 1.41 , $p < 0.05$; Variance= 6.06 ± 1.81 , $p < 0.05$) and somatosensory-impairment (RMS= 4.03 ± 7.71 , $p < 0.05$; Variance= 5.80 ± 2.73 , $p < 0.05$). COP RMS was elevated significantly

($p < 0.05$) above QS and somatosensory in the somatosensory/vestibular-impairment condition (8.51 ± 3.17 , $p < 0.05$). *Conclusions.* Sleep deprivation may affect balance control. These interpretations are supported with weak statistical evidence, and must be considered tentatively.

Introduction

Data from the 2002 Canadian Community Health Survey (CCHS) found that 18% of individuals receive less than 5 hours of sleep per night—much less than the recommended 8 hours (1). The impairment of central function accompanying sleep deprivation is detrimental to many aspects of life: over 60% of drivers report driving while sleepy, causing 20% of severe motor vehicle accidents in the United Kingdom (2). Suboptimal performance of functional tasks of daily living can threaten safety in demographics such as surgeons, pilots, and construction workers. University students, in particular, often sacrifice adequate sleep to meet academic demands.

Marked decreases in cognitive and attentional performance (e.g. alertness, coordination, and judgement) have previously been demonstrated after 24 hours of sustained wakefulness (3). Although the effects of sleep deprivation on brain activity have been studied for centuries (3), resultant balance deficits are not well documented. Postural control is a determinant of functional independence and is crucial for assessing an individual's postural stability (4). Numerous studies have reported impaired postural control following sleep deprivation (2, 5, 6). Originally, it was believed that

postural control was an autonomic process unaffected by changes in cognitive activity (6, 7). However, studies have shown that postural control demands cognitive function, especially when the sensory system(s) are affected (6).

Posture is controlled by an elaborate sensorimotor integration network (7). Separate internal representations of external stimuli feed into a single postural control mechanism with the appropriate weighting of each input (7). Implementation of several control functions into one mechanism requires a sensorimotor integration (7). This integration is based on the fusion of sensory cues rather than on a single sensory input (7). Figure 1 illustrates the three major sensory inputs affecting postural control: visual, vestibular, and somatosensory systems (7). Vision provides information about the location, direction, and speed of movement within the environment (8). The vestibular system is located in the inner ear and provides information about accelerations of the head (8, 9). The somatosensory system provides information regarding body contact and position. Cutaneous receptors are sensitive to any contact and relay these changes (such as temperature, pressure, and vibration) to the central nervous system (8). Combined, the visual, vestibular, and somatosensory pathways supply the feedback required for sensorimotor integration and postural control.

Clinical and rehabilitation centers use various balance tests to assess patients' postural control. Appropriate tests for healthy adults must impair two of the three sensory systems in order to generate observable changes in balance (10, 11). Spirduso (8) determined that vision can compensate for deficits in vestibular function during sensory-impaired quiet standing. However, compensation is not always possible during loss (or fragmentation) of multiple-system sensory feedback (8). Inducing sleep deprivation in individuals who exhibit poor postural control could further result in increased numbers of slips, trips, falls, and their associated psychological consequences (4).

Successful postural control involves integration of multiple sensory inputs to produce appropriate motor output. Previous investigations of sleep deprivation and postural control have overlooked the integration of multiple sensory inputs, using visual impairment as an experimental paradigm. The protocol exhibited by Shumway-Cook and Horak (12) is a reliable clinical

assessment of balance (13), which may be supplemented with vestibular-intervening "head-tilt" (14) to determine the effects of all three major sensory systems associated with balance.

Studies have used various measurements to assess postural control. Center of pressure (COP) is the weighted sum of ground reaction forces (4); body sway has been estimated from COP measurements (11). It is imperative that COP measurements be made in both anterior-posterior (A/P) and medio-lateral (M/L) directions because humans use different muscle strategies to correct respective perturbations (4). An increase in COP deviations in either direction may indicate negative impacts of sensory impairments on the central nervous system's (CNS) control of balance.

The purpose of this study was to compare the effects of sleep deprivation and adequate rest on postural control. This may provide valuable insight regarding the integration of visual, vestibular, and somatosensory feedback with motor output. It is hypothesized that significant increases in COP deviations will occur after sleep deprivation and will be exacerbated by the impairment of two or more sensory inputs.

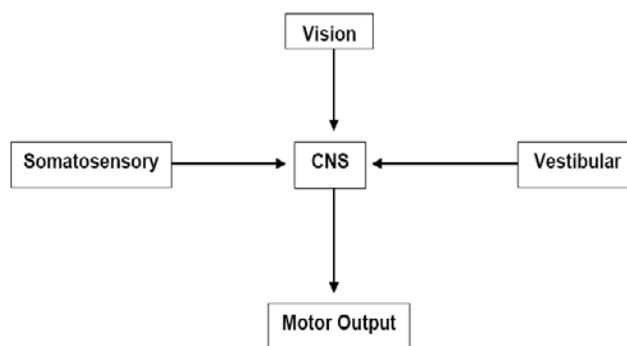


Figure 1. *Schematic Diagram of sensorimotor integration of vestibular, visual, and somatosensory afferent feedback to the central nervous system (CNS).*

Methods

Subjects

Four healthy adults participated in the present study (summary statistics, Table 1).

Table 1. *Subject summary statistics. Note that arousal time equals the hours of sustained wakefulness prior to “sleep deprivation” condition testing. Sleep time equals number of hours slept in the night prior to rested condition testing.*

Subject	Height (m)	Mass (kg)	Age (years)	Activity (h/wk)	Arousal Time (h)	Sleep Time (h)	Sex
1	1.75	65.7	21	7	28.0	7	F
2	1.61	55.0	22	5	27.0	8	F
3	1.78	75.0	22	8	30.0	6	M
4	1.80	80.0	21	7	34.5	8	M
Mean ±	1.74±	68.93 ±	21.50 ±	6.75 ±	29.88 ±	7.25 ±	
SD	0.09	11.0	0.58	1.26	3.33	0.96	

Materials and Experimental Setup

Equipment and Data Collection. Force (COP) data were sampled for 40 s at a sampling rate of 64 Hz from a Kistler force plate (model 9287B). The force plate signal was amplified (National Instruments), analog to digitally converted (National Instruments), and visualized using LabVIEW (National Instruments).

Experimental Set Up. A dark screen was situated 2 m away from the closest edge of the force plate (5). Brightly contrasted markers were fixed at subjects' respective eye levels on the screen for visual fixation during visually unimpaired trials. Before trials, subjects' footprints were marked with tape on the force plate (at toes and heels) to ensure consistent placement and alignment of feet. Socks were worn (to ameliorate confounding due to foot cooling) and subjects' anterior surfaces faced the screen in all trials. Markers were placed on the ceiling to create a visual fixation point for the vestibular interference condition (Ve).

Procedures

Design. Eight trials (described in detail below) were performed on each testing day to assess standing balance. Subjects were assessed on two testing days separated by one week for a total of sixteen tests for each subject. Two of the four subjects were sleep deprived (mean arousal time=29.88 ± 3.33 h) during each testing session. All subjects performed the quiet stance (QS) condition first. Other testing interventions were randomized using a random number generator (Microsoft Excel 2007) and performed intermittently with three minutes of rest to minimize the occurrence of fatigue (4).

Subjects were told to stand “naturally”: (a) without initiating voluntary movement and (b) minimizing attention to voluntary control of posture.

QS: Subjects stood erect with feet aligned according to force plate markings and were told to focus upon the visual fixation point two meters ahead. Arms were placed quietly at sides.

Visual impairment (V): Blindfolded, subjects adhered to QS protocol.

Somatosensory (S): Standing on a large square of foam subjects adhered to QS protocol.

Vestibular impairment (Ve): Subjects assumed quiet stance position and maximally extended their necks. During trial, subjects fixated on a point placed on the ceiling.

Visual impairment/Vestibular (VVe): Blindfolded, subjects adhered to Ve protocol (omitting visual fixation).

Vestibular and Somatosensory impairment (VeS): Standing on foam, subjects adhered to Ve protocol.

Visual and Somatosensory impairment (VS): Blindfolded, subjects adhered to QS protocol while standing on foam.

All impairments: Blindfolded, subjects stood on foam and adhered to Ve protocol.

Calculations.

In both A/P and M/L directions, COP Variance (eq. 1) and COP RMS (eq. 2) were calculated.

$$RMS = \sqrt{\left(\frac{1}{n}\right) \sum_{i=1}^n (\text{Normalized } COP_i^2)} \quad (\text{eq. 1})$$

$$COP \text{ Variance} = \frac{\sum_{i=1}^n (COP_i - \overline{COP})^2}{(n - 1)} \quad (\text{eq. 2})$$

Statistical Analysis.

Two-way analysis of variance (ANOVA) was used to assess the significance of effects between the sleep (or deprived) condition and sensory intervention conditions. 2 X 8 (Sleep X Sensory condition) ANOVAs with repeated measures on both factors were performed with each of the four dependent variables (M/L, A/P, RMS, and Variance). Paired t-tests were then performed to measure statistical significance between sensory interventions within sleep, or deprived, conditions.

Results**Sleep Deprivation and Rested Conditions**

Neither ANOVA, nor independent t-tests demonstrated any significant differences between sleep deprived and rested conditions within the sensory interventions. A summary of these data can be found in Figure 2.

Rested Condition

All sensory interventions were statistically similar within the rested condition. No significant changes from quiet stance were found through independent t-tests (refer to Figure 2).

Sleep Deprived Condition

Since ANOVA analyses were consistently underpowered, pairwise comparisons (t-tests) with rested and sleep deprived conditions were performed. Figure 3 describes significant changes between sensory interventions within the sleep deprived condition.

Medio-Lateral Direction. COP RMS and Variance of COP fluctuation magnitudes were significantly greater medio-laterally in the ALL condition ($t=4.615$, 3df, $p<0.05$)

and $t=4.274$, 3df, $p<0.05$) than in Quiet Stance. Also, COP RMS was significantly greater in the Visual Vestibular impairment condition ($t=3.193$, 3df, $p<0.05$) than in Quiet Stance.

Antero-Posterior Direction. Similar to the M/L direction, COP RMS and COP Variance were significantly greater in ALL ($t=4.678$, 3df, $p<0.05$ and $t=3.839$, 3df, $p<0.05$ respectively), compared to Quiet Stance. These values were both significantly greater than respective measurements in Visual impairment ($t=3.638$, 3df, $p<0.05$ and $t=4.209$, 3df, $p<0.05$) and Somatosensory ($t=6.521$, 3df, $p<0.05$ and $t= 4.182$, 3df, $p<0.05$). COP RMS was elevated significantly ($p<0.05$) above both Quiet stance ($t=3.236$, 3df, $p<0.05$) and Somatosensory ($t=3.726$, 3df, $p<0.05$) in the Vestibular/Somatosensory condition.

Discussion

The aim of the present study was to evaluate the integration of visual, vestibular, and somatosensory feedback on postural control during conditions of adequate rest and sustained wakefulness. It was hypothesized that sleep deprivation would result in greater COP RMS and COP Variance. ANOVA did not reveal a significant effect of sleep deprivation on measures of postural control during sensory intervention. Since the ANOVA analyses were consistently underpowered, pair wise comparisons (t-tests) within rested and sleep-deprived conditions were performed. Our findings must therefore be tentatively interpreted. These analyses revealed that: (i) a minimum of two sensory systems must be impaired at once to observe postural control deficits; and (ii) one of the two (minimal) sensory impairments must target vestibular feedback. Our results suggest that during a sleep-deprived condition, there may be greater demands placed on sensorimotor integration of visual, vestibular, and somatosensory feedback.

Impairment of Two or More Sensory Cues Increases Fluctuation of COP during Sleep Deprivation

Paired t-tests revealed that impairment of two (or more) sensory systems increased measures of postural sway. Figure 2 indicates that the greatest deviations in COP displacement (relative to QS) were observed during ALL, within the sleep deprived condition. Figure 1 illustrates a basic schematic of sensorimotor integration

during stance. The impairment of sensory information (especially from somatosensory and vestibular inputs) results in the provision of fragmented information by these sources to the CNS (note that visual input can be removed entirely). The CNS may possess a high capacity for generating effective motor commands from fragmented information. However, during sleep deprivation the CNS may demand greater cognitive attention to sustain adequate sensorimotor integration. Using brain imaging and cognitively demanding tasks (mathematical), Thomas *et al.*, (3) found that sleep deprivation markedly impaired attentional capacity and general cognitive function, especially in regions mediating sensorimotor integration. These authors also noted that interference with more than one source of sensory information increased the neural demands for sufficient integration (3). If sleep deprivation impairs attentional

capacity (in the form of neural activation capabilities) (3), it is possible that drastic fragmenting of sensory information (e.g. experimental interventions of the present study) cannot be effectively integrated, resulting in diminished postural performance.

Vestibular Afferent Feedback May be Enhanced during Sustained Wakefulness

In the present study, multiple-system sensory interference reduced performance of standing balance when vestibular feedback was impaired (i.e. VVe, VeS, and ALL conditions). One of two inferences may be drawn: (a) that during sleep deprivation, the influence of vestibular sensory feedback on generation of motor commands is greater than that of somatosensory or visual receptors, or (b) experimental interventions impaired vestibular feedback to a greater extent than

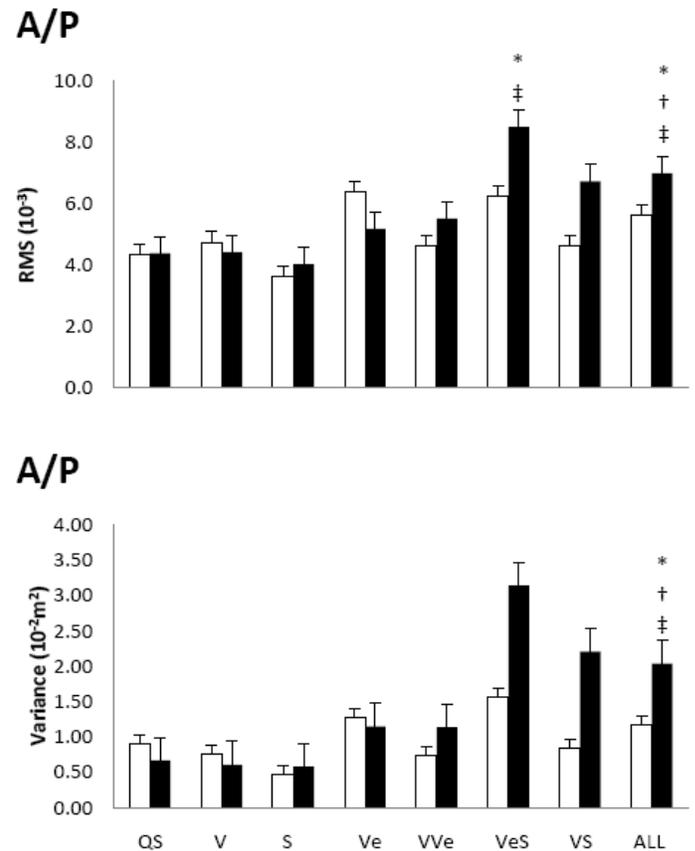
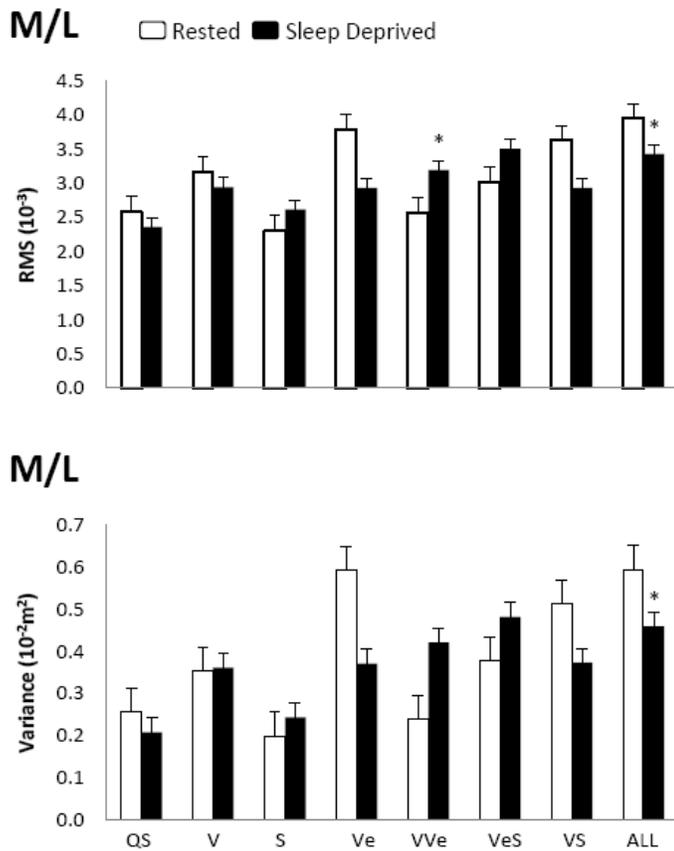


Figure 2. COP RMS and COP Variance data for sensory interventions (quiet stance, QS; visual impairment, V; somatosensory, S; vestibular impairment, Ve; visual and vestibular impairment, VVe; vestibular and somatosensory impairment, VeS; visual and somatosensory impairment VS; all-system impairment, ALL) within sleep deprived and rested conditions. Top row refers to COP RMS, bottom row refers to COP Variance. White bars represent data from rested condition; dark bars display data from sleep deprived condition. Note that two-way ANOVA did not show statistically significant effects between rested condition and sleep deprivation condition. Statistical significant is displayed from paired *t*-tests within rested or sleep deprived conditions (*significantly greater than QS, $p < 0.05$; †significantly greater than V, $p < 0.05$; ‡significantly greater than S, $p < 0.05$).

somatosensory input. This potential discrepancy in sensory impairment magnitudes constitutes an important limitation to our experimental method. Although shown to effectively impair vestibular input to the CNS (15), the comparability of this technique with somatosensory-impairing interventions is unknown to the authors. However, previous studies have alluded to the particular importance of vestibular sensory information during sleep deprivation. The vestibular apparatus are increasingly sensitive to stimulation during sustained wakefulness. Quarck *et al.* (16) demonstrated an increased gain in the vestibulo-ocular reflex loop following 26-29h of sustained wakefulness (for review of vestibulo-ocular reflexes, see 17). Oosterveld (18) also identified that sleep deprivation “renders people more susceptible to motion sickness,” which results from an increased vestibular organ sensitivity. In conjunction with these pieces of evidence, our data—although based on a very small sample—may suggest that during and/or after sleep deprivation, vestibular sensory feedback becomes increasingly important relative to somatosensory and visual feedback.

Visual and Somatosensory Information may be Down-Regulated during Sustained Wakefulness

Controversy exists surrounding the importance of visual input for effective sensorimotor control of posture and balance (2, 5, 19, and 20). In these investigations, there appeared to be a time-dependent effect of sustained wakefulness on the influence of visual cues. When visual input appeared critical for effective sensorimotor integration, subjects were deprived of sleep for a much shorter period of time (12 hours) than studies supporting the contrary (approximately 24 hours of sustained wakefulness). It is possible that after a critical duration of sustained wakefulness, the usefulness of visual feedback decreases. Studies have found that after sleep deprivation, oculomotor performance (21) and near and far vision (22) are impaired compared to conditions of adequate rest. Therefore, higher sensorimotor integration centres may recognize these impairments and down-regulate the importance of visual feedback.

Somatosensory afferent feedback did not appear to alter the performance of postural balance during the sleep deprived condition. Previous investigators have shown that anesthetic blockade of somatosensory information did not result in temporal or qualitative abnormalities in postural responses to sway (23). The

authors concluded that the remaining fragmented information provided to CNS integration centres was sufficient to maintain high performance of postural balance. Our somatosensory-impairment intervention merely *reduced* the somatosensory feedback. Sensory cues such as temperature, pressure and vibration may not have been adequately controlled for by merely standing on foam. Notwithstanding, in light of the complete blockade administered by Horak *et al.* (23), our (insufficiently impairing) intervention would not likely produce contrasting results. It is possible that after sleep deprivation, somatosensory afferent feedback, perhaps similar to visual feedback, becomes down-regulated by higher CNS integration centres. It is also possible that somatosensory feedback is usually down-regulated, relative to vestibular and visual information.

Adequately Rested, Healthy Adults may have the Capacity to Integrate Fragmented Sensory Information

Paired t-tests revealed no significant difference between sensory interventions within the adequately rested condition. Many studies which have shown differences between sensory-impairing interventions in adequately rested participants have used subjects from aged and/or clinical populations (23, 24). However, aging populations have been shown to lack attentional capacity compared to young subjects (25); and as mentioned, diminished attentional capacity may reduce the fidelity of sensorimotor signals integrated from fragmented sources. Moreover, individuals undergo significant neuromuscular changes with age (26, 27). Clinical populations may possess disturbances to central oscillators governing motor unit activation patterns, impairing sensorimotor efferent signals (28). Since young individuals possess greater CNS integrative capacity and sufficient peripheral support (muscles, motor unit organization) to execute efficient sensorimotor control of standing balance, it is not surprising that sensory-impairment interventions did not decrease the performance of standing balance from QS during adequately rested conditions.

Limitations and Future Work

Analysis of variance (ANOVA) was underpowered in the present study, suggesting that a greater sample size should be employed for clarification of potential effects observed using paired t-tests. Given

the limited sample size and power of this study, corrections for multiple comparisons were not performed. Quantification of interventional sensory signal fragmentation, and relative sensory influences on sensorimotor integration cannot (to our knowledge) yet be quantified. Therefore, understanding down-regulation of sensory feedback is, and will remain speculative practice until reliable measurement techniques are developed.

We observed some potentially interesting findings with implications for sensory integration in individuals, such as drivers, medical personnel, and students, who may experience balance perturbations after sleep deprivation. However, it is important to acknowledge that our measures of balance and postural control are interpreted from COP data exclusively. To provide a more complete dataset for the understanding of postural control, it would be more appropriate to evaluate the relationship between the whole-body centre of mass (COM) and the COP (11).

We have presented evidence from prior investigations suggesting the importance of attentional capacity and demands for effective, high performance, sensorimotor integration. Our protocol attempted to control for increased focus on postural steadiness by emphasizing subject relaxation and lack of attention to sway during stance. Through these instructions, we attempted to obtain data representing “natural” stance and its sensorimotor integration. However, it is likely that subjects attempted to correct postural shifts voluntarily as a secondary task technique. These conscious increases in attention to posture may confound our data which have been shown to have negative effects on balance control. To our knowledge, these variables cannot be controlled in a laboratory setting.

Conclusions

The effects of sleep deprivation on posture are controversial, especially as they pertain to multiple-system sensorimotor control of balance. Our study was the first to investigate the effects of multiple, combined sensory-impairment interventions across conditions of adequate rest and sleep deprivation. Analyses of variance indicated a non-significant effect of sleep across sensory interventions. However, these tests were consistently underpowered and may have overlooked valid physiological phenomena. Further statistical

analyses within rested and sleep deprived conditions demonstrated significant decreases in control of balance within the sleep deprived state. Notably, (i) more than one sensory system (of vestibular, somatosensory, and visual) must be impaired simultaneously to produce observable deficits in postural control, and (ii) impaired postural control was only observed during vestibular intervention trials. These trends may suggest an up/down-regulation strategy employed by the CNS to maximize control of balance. However, the statistical analyses upon which these interpretations rest demand extreme caution in drawing conclusions. Increases in sample size are required to increase the power and meaningfulness of the present study. Future investigations should include individuals who exhibit impairment of a sensory system(s) to determine if sleep deprivation may affect these populations to a greater extent.

Acknowledgements

The authors would like to thank Dr. Jim Dickey for his guidance, thorough reviews, and support throughout this study. We are also grateful to Ryan Frayne for his technical and lab support.

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