THE RELATIONSHIP BETWEEN SOUND INTENSITY AND THE CENTER OF BALANCE

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Abstract

Daily activities require the proper coordination between sensory systems, brain integration, and muscular movements. A deviation in any of these systems may slightly or severely disrupt the body's sensitive homeostatic levels. In this experiment, we investigated the relationship between the sensory processing systems, muscle activity, and controlled balance. By administering increasing sound intensity directly into the subject's ears, we explored whether there was a correlated deviation from the center of balance. The sense of sight was removed in order to focus on the relationship between auditory stimulation and muscle reactivity. Balance was recorded on a Wii Balance Board, muscle activity was measured using Electromyography (EMG), and sound was regulated through noise canceling headphones. A pulse oximeter was used to detect instantaneous changes in heart rate as a result of the administration of sound at different intensities. Background research has shown evidence that at certain thresholds, sound may influence and alter core balance. We hypothesized that as sound intensity increased, leg muscle activity would increase, and a resulting deviation from the center of balance, measured by path length, would also increase. Our results showed that minimal auditory stimulation increased overall balance resulting in minimal path length movement. However, at and above a sound threshold around 100 mV, an increase in both muscle activity and path length was observed, although no significant relationship was determined. Investigation into how sound intensity and balance are linked must be researched in further detail to determine whether a correlation exists.

Key Word List
Auditory, Balance, EMG, Sense, *Proprioception, Stability, Vestibular, Impulse*

Word Count: 3031

Introduction

Balance plays a role in establishing and maintaining stability in movements, providing a sense of equilibrium as well as aiding in proprioceptive accuracy. It is more difficult to achieve balance without the successful integration of the auditory, vestibular, and muscular systems[27]. A disturbance in any of these three systems may lead to an equilibrium shift, resulting in the need to reestablish postural stability. Thus, the cooperation of independent systems plays a role in establishing stability.

The auditory system consists of the outer, middle, and inner ear. Specifically, hearing is controlled by the cochlea, which is found in the inner ear and formed by the bony labyrinth. When a sound wave is received, auditory ossicles transmit vibrations of the tympanic membrane to the cochlea[2]. The cochlea converts this sound pressure into electrochemical pulses. Within the cochlear duct lies the organ of Corti and its hair cells, which are bathed in endolymph fluid. The organ of Corti contains four rows of hair cells, one inner layer and three outer layers. Above the hair cells lies the endolymph filled tectorial membrane[26]. When the hair cells are agitated by fluid movement, electrical impulses are sent to the cochlear division of cranial nerve VIII, ultimately leading to proprioception[21]. These electrical impulses stimulate the opening of nonselective cation channels that depolarize the hair cells. This causes the release of an excitatory neurotransmitter to nerve fibers, resulting in the transduction of sound.

The vestibular system consists of five organs; three semicircular canals that sense angular acceleration, and two otoliths. The two otoliths are comprised of an utricle and a saccule that are both sensitive to gravity and linear acceleration[33]. Any acceleration perceived by the ear causes the endolymph to move and the upright hair cells to consequently shift. Hair movements are transmitted as impulses and are sent to the CNS by cranial nerve VIII. Upon receiving a stimulus, the body reestablishes homeostasis by moving the skeletal muscle to regain balance[52].

In addition, the muscular system is involved in the maintenance of balance. Nerve stimulation at the neuromuscular junction can cause striated muscle to contract, resulting in a desired movement. Skeletal striated muscles and joints contain sensory receptors called proprioceptors that detect body movements and subsequently send signals to the brain to register the motional changes[20]. The brain integrates these signals as well as signals from the vestibular system, which generate a sense of position in space.

The aim of this study was to further investigate the extent of the interactions between the vestibular and auditory systems and the resulting effects on the muscular system due to a sound disturbance. Although the organs involved in these systems are in close proximity, little is known about how they interact with one another. We hypothesized that an increase in sound intensities would positively correlate with disruptions in the center of balance. We recorded the deviations from the center of balance from a baseline measurement using a Wii Balance Board (WBB) and engineering software. Furthermore, an EMG and a pulse oximeter was used to measure muscle activity and heart rate respectively. The WBB has previously been shown to accurately measure static center of balance stability[9]. In this study, we defined balance as the path length measured by the WBB. A long path length would mean low balance, whereas a short path length would indicate high balance. Also, in order to eliminate the variable of sight, we used a blindfold, as vision works with the vestibular system to maintain balance. The results of our experiment may provide insight into the effects of sound on balance, leading to improved techniques in the field of rehabilitation and recreational activities.

Methods

Participants were tested in compliance with the subject testing policies and regulations. Each participant was guided into an empty, quiet room and asked to remove their shoes in order to remove the variability of shoe dependent postural stability. The dominant leg was determined by an experimenter gently pushing the subject. The leg that the subject steps forward with first was recorded as the dominant leg for electromyography (EMG) purposes. The EMG was connected to a computer desktop using Biopac Student Lab 4.0 Software. Three electrodes were connected to the subject's dominant leg via electrode gel in three different positions: inner-side of the ankle, middle of the calf, and directly below the knee. These electrode positions were kept consistent between subjects in order to measure the movement of the same muscles in every participant. The EMG was calibrated with the Biopac Software before experimental measurement. Beats per minute (BPM) was measured using a pulse oximeter. The Nonin Pulse Oximeter was turned on and placed on the subjects left index finger. Finally, a Wii Balance Board (WBB) was connected via a Bluetooth to a custom MATLAB R2011a program. After the program "bbercord_1_5.m" and the Wii Balance Board (WBB) was calibrated, the setup tracked and recorded a subject's center of balance (COB) location over a period of 20 seconds. A function generator was used in order to produce the desired noise frequency at varying intensities.

Once the EMG, pulse oximeter and WBB are set up, controls were established. A baseline balance measurement was then obtained and used as the negative control. Afterwards, this baseline was measured by having the subject blindfolded with no sound coming from the sound canceling headphones. The participant stood on both feet for this and all of the experimental procedures as well. This value demonstrates a participant's normal balance ability. The positive control was established by having the subject stand on their non-dominant leg, while blindfolded to show how a deviation of balance records on the EMG, pulse oximeter, and WBB. Data from the positive and negative controls was first obtained before beginning subsequent experimentation.

For sound intensity experiments, a blindfold was used for each subject in order to remove the variable of sight. The subjects were exposed to 5 different intensities of sound established by manipulating the voltage output from the function generator. We were unable to directly measure sound intensity due to equipment limitations, thus voltage changes were used as the manipulated variable; the greater the voltage, the greater the sound intensity. It was important to note that voltage and sound intensity were not linearly related, so the intensity difference in sound intensity between each interval was not constant. Voltages of 0mV, 50mV, 100mV, 150mV, and 200mV, respectively, were used. The sound was emitted through noise canceling Bose QuietComfort15© headphones. The frequency of the emitted sinusoidal wave was held constant at 500Hz, which is well within the normal range of human frequency detection of 20Hz to 20kHz[51], and was subjectively chosen. Each sound was played for 20 seconds. Throughout each 20 second trial, the EMG, pulse oximeter and WBB recorded muscle movement, heart rate, and deviation from center of balance, respectively. Immediately before and immediately after the administration of the sound, the participant's BPM was recorded. Biotech 4 Biopac software and the bbercord_1_5.m program recorded the muscle activity and COB movements respectfully. A second MATLAB program, "pathlength_calc.m," was then used to compute the distance traveled by an individual's COB. Each subject's path length was used to determine postural stability along with calf muscle activity.

Materials

- EMG and Biotech 4 Software (Biopac Systems, Inc., BIOPAC Part. No. MANBSL4, Student/Bookstore Version)
- Sound cancelling headphones (Bose, model: QuietComfort15©)
- Pulse Oximeter (Nonin Medical Inc., Model #9843)
- Wii Balance Board (Obtained from UW-Madison Biomedical Engineering Department, Nintendo brand)
- Function generator (Agilent, model number 33220A, obtained by the UW-Madison Physics Department)
- Custom-built adaptor to connect the headphones to the function generator (2mm jack to BNC RCA male output, made by UW-Madison physics department)
- Matlab R2011 Software (Obtained from UW-Madison Biomedical Engineering Department)
- pathlength_calc.m code (path length analyzing code, written by co-author Jake Tokar)
- bbrecord_1_4.m code (Links WBB to MATLAB software, obtained from the Neuromechanics Laboratory in the Department of Integrative Physiology at the University of Colorado-Boulder)
- Human Subjects (25 Total)
- Consent form (Draft by UW-Madison Physiology 435 Department, edited by lab group)
- Heart Rate (BPM) tracking sheet (created lab group)
- Blindfold
- Purell disinfectant wipes

Results

To ensure our testing procedure could properly detect a loss in balance, a comparison between the positive and negative control had to be made. It was hypothesized that a loss in balance would be signified by an increase in not just COB path length and EMG muscle activity, but also heart rate when compared to a balanced state. Although the heart rate data showed no correlation to loss of balance, the path length and muscle activity both increased from the negative to positive control. A t-test was performed to test the significance of this increase and it was found that at a 95 percent confidence interval, both results can be considered significantly different, demonstrating the validity of the two tests. A sample of the raw data for one of the subjects is illustrated in Figure 1 where a clear increase in both COB path length and EMG activity can be seen when a subject loses his/her balance.

Once each subjects' COB path length was calculated, the results were normalized in reference to the negative control distance for each respective subject, allowing comparative analysis between each condition. The normalized values were then averaged for each condition. After averaging the path length results, we noticed a general trend. From the negative control (0 mV) to 50 mV, a general decrease in path length was observed and from 50 to 100 mV, the path length increased slightly. However, from 100 to 150 mV and continuing on through 150 to 200 mV, a general increase in path length was observed, with the average distance for the greatest sound intensity being greater than the negative control. This trend can be seen on the orange plot of Figure 2.

To further test the validity of this a trend, an ANOVA test was employed to compare each of the conditions to one another and each control. It was found that at a 95 percent confidence interval, none of the changes observed between each condition were statistically significant except for the positive control. Specifically, when the positive control was removed for a second ANOVA test, the p-value increased from 6.2E-36 to 0.72, indicating that the trend observed between the experimental conditions was insignificant.

An EMG was used to measure the change in leg muscle activity for each participant during each of the five sound intensities, 0 to 200 mV in 50 mV increments. Electrodes were placed on the legs and over each 20 second interval muscle movements were recorded on an EMG curve. The data were then analyzed by measuring the area beneath the produced curve. Each experimental result was then normalized by that of the negative control, yielding comparable data points. An ANOVA test was used to test the significance of any changes in muscle activity from one condition to the others.

It was hypothesized that an increase of sound intensity would negatively affect balance and increase muscle activity, ultimately increasing the area beneath the curve. Overall, muscle activity does increase from 0mV to 200mV, although not linearly. When sound was increased from 0 to 50mV, muscle movement generally remained steady, with the average area increasing from 5.48 to 5.56 mV•s. When sound was again increased by 50mV, to 100mV of sound, the value decreased to 4.48mV•s. When increased to 150mV the area increased to 5.38mV•s, and again increased to 8mV•s at 200mV. Table 1 displays the average muscle activity for each sound intensity as well as normalized averages, allowing for simpler comparison to be made. The normalized values were also plotted on the blue line on Figure 2. After performing an ANOVA test on the normalized EMG results, it can be said at a 95 percent confidence interval that the only significant change in muscle activity was for the positive control.

After analyzing the data recorded from the pulse oximeter, no significant relationship between the intensity of sound and heart rate change was found. Heart rate was taken before and after the sound was administered to each subject. The difference in BPM was calculated for each sound from 0 to 200 mV. The difference in BMP was used to account for the differing resting heart rates between participants. Once difference in BPM for each sound and subject was found, the data were analyzed by taking a baseline value (0 mV, the negative control) and calculating the change between the baseline and each respective sound administered.

It was originally hypothesized that the rate of change in BPM would have a positive linear relationship with increasing sound intensity. Our results showed a large variation between each subject's BPM results for each sound intensity. As a result, this did not follow a linear trend. On average, the change in BPM between 0 and 50mV increased 1.36 beats. From 0 to 100mV, 0 to 150mV and 0 to 200mV, BPM changed 1.64, -0.16, and .96 beats, respectively as shown in Table 2 and Figure 3. Two subjects, 8 and 14, followed an inversely proportional trend, with changes of BPM decreasing with increasing sound intensities.

Discussion

Normal postural control is based on external sensory information interpreted by various bodily systems, such as the vestibular system. Previous studies have indicated that auditory cues may also play a role in postural stability. However, a clear relationship between the two is still being investigated today. The current paradigm involves three factors influencing postural stability, including vision, proprioception, and vestibular sensation [15]. In this study, these three factors were modified throughout the procedure in order to determine a clear relationship between auditory biofeedback and postural stability.

We hypothesized that increased sound intensity alone would lead to a decrease in balance. After analyzing our data, a linear relationship was not found between postural stability and auditory stimulation. In fact, our results suggest that low sound intensities increase balance, while high sound intensities decrease it. Previous studies have shown that auditory biofeedback can increase postural stability in individuals with bilateral vestibular loss[46]. These findings would support our results and explain why weak auditory stimulation between 0mV and 100mV leads to an increase in balance, while strong auditory stimulation between 100mV and 200mV inhibits it. This trend might suggest the existence of a sound intensity threshold. Future studies will aim to further explore this threshold of sound needed to give optimal stability. Similarly, balance and muscle activity seemed to be directly correlated when using sound intensities greater than 100mV, but had an inverse relationship while using sound intensities less than 100mV according to our results. However, these trends did not demonstrate statistical significance.

Heart rate also portrayed a nonlinear relationship in regards to sound intensity and balance. It was hypothesized that a decrease in balance would lead to an increase in muscle activity, which would in turn increase heart rate. However, our data suggest no correlation between muscle activity or balance with heart rate. These results may be due to inaccurate pulse oximetry instruments used in the study.

The maximum intensity used for our experimental data was 200 mV. This maximum threshold was set by the authors by determining the highest sound intensity that could be used, while causing only a slight, short term, discomfort level to the subjects. During the experiment, sound intensities were increased in 50mV increments from 0 to 200mV for each participant, rather than randomly distributed. Having sound intensities randomly distributed, instead of sequentially, may have eliminated the subject from becoming accustomed to an increase in sound. However, large sound intensities might cause short term desensitization of the ear[15], which is why intensity was not randomized.

Due to the limitation of materials and small sample size, chances of error may have increased in many areas of the study. Participants were asked to stand throughout the duration of testing, lasting five minutes on average. This time frame may have led to fatigue of leg muscles, skewing our results, leading to an increase in heart rate, muscle activity, and imbalance. Also, our experimental procedure did not account for a difference in balance between each subject. Each subject could present a different technique for balance, or have a pre-existing condition that might be linked to a balance deficiency, regardless of sound stimulation. Other possible sources of error that may have been encountered include EMG electrode positions that could have varied per subject, altering readings of muscle stimulation. The pulse oximeter also gave delayed measurements, which prevented us from getting a measurement at a certain point of time. With a better understanding of how hearing and balance are integrated, treatments for brain injuries and vestibular disorders can be tailored to address patients' specific needs and quicken recovery. Using auditory stimulation during therapy may have the potential to aid in regaining postural stability and rebuilding balance[46]. A better understanding of both hearing and balance can have various clinical implications, such as including treatment of a patient's hearing ability in order to improve their overall balance.

Balance requires accurate brain reception, integration, and response to sensory organ stimuli. The way in which different sensory stimuli is integrated at different times is situational[45]. In addition, the sensory inputs that contribute the most to postural stability can change depending on the specific environmental conditions. For example, sense of sight was eliminated in this experiment through the use of a blindfold. Therefore, a greater emphasis on proprioception was required in order to compensate for the loss of sight. It is clear that further studies must be conducted to elucidate the complexities of postural stability control.

Acknowledgements

We would like to thank the 2014 Physiology 435 staff for their help in providing lab equipment and guidance throughout our experimental process. We would also like to specifically thank Yang Yang with the UW-Madison Statistics Department and UW-Madison Physics faculty, Dr. James Reardon and Steve Narf, for their contributions with the sound equipment and for making the needed adaptors to use said equipment. Finally, we would like to thank Dr. Daryl Thelen and Kyle Jamar of the UW-Madison Biomedical Engineering department for allowing us to borrow a Wii Balance Board as well as answering any and all questions regarding the program and code.

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Figures and Tables

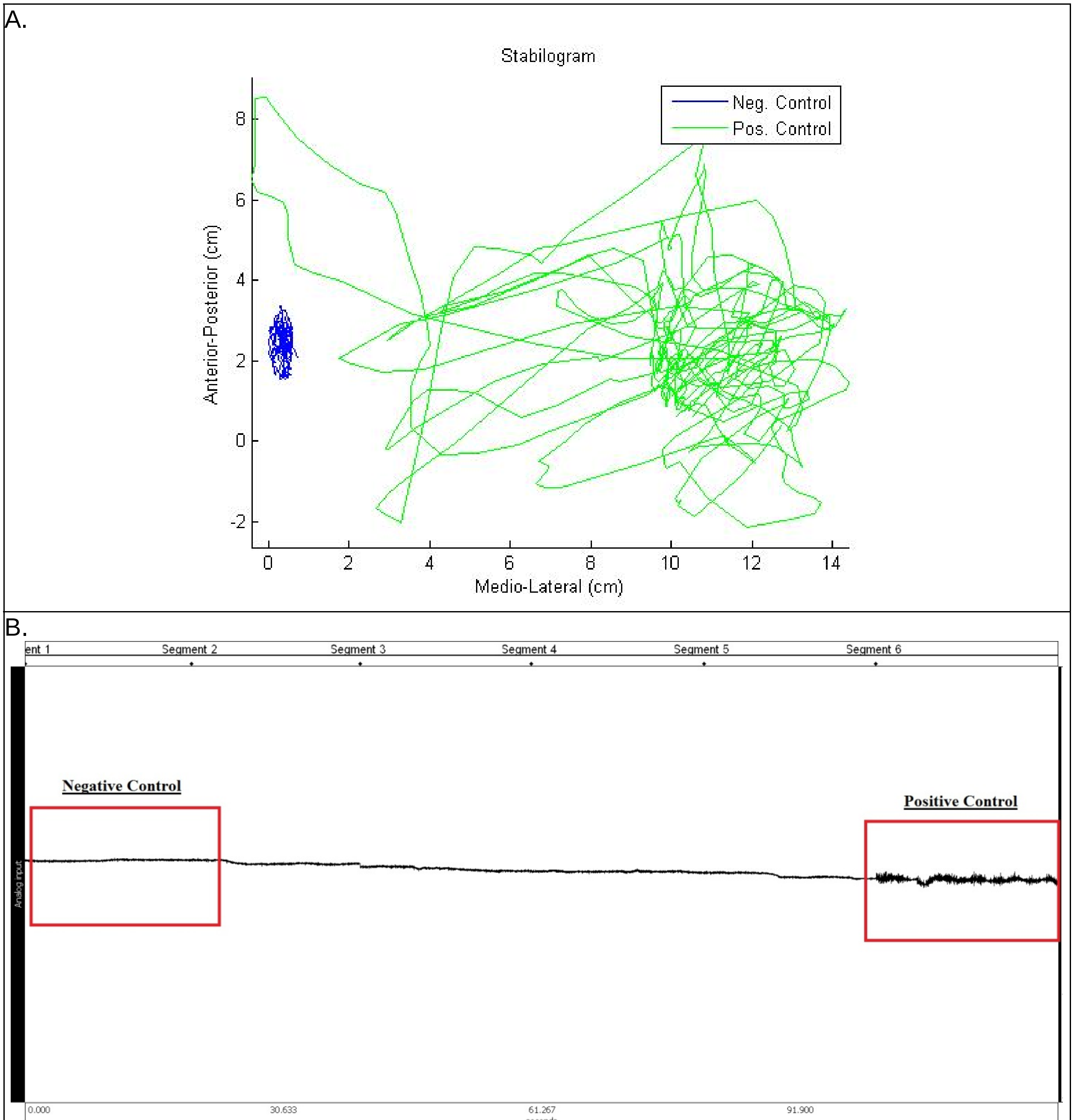

Figure 1: *Control Validation* – As seen in part (A) the positive control COB path length is much larger than that of the negative control, demonstrating the Wii balance board program can detect decreased balance. Similarly, in part (B) the EMG of muscle activity for the positive control was greater than the negative control as well.

Figure 2: *Normalized Path Length and EMG* – The orange plot is of the normalized COB path length averages for the negative control (0 mV) and each experimental condition. Additionally, The Blue plot represents the normalized EMG of calf muscle activity.

Intensity (mV)	**0**	**50**	**100**	**150**	**200**	**+ Cont**
Activity (mV/s)	5.48	5.56	4.89	5.38	7.99	28.7
Activity (norm.)	1	1.59	1.34	1.55	1.84	8.00

Table 1: *Average EMG* – It was found that muscles were generally more active as sound intensity increased.

Figure 3: *Average BPM Change* – The trend line shows no significant pattern in the change in BPM as sound intensity increased. This was made even more evident with the R^2 value of 0.25934, which was far too low to represent a trend.

Baseline	**Δ 50 mV**	**Δ 100 mV**	**Δ 150 mV**	**Δ 200 mV**	**Δ + Cont.**
0	**1.36**	**1.64**	**-0.16**	**0.92**	**1.44**

Table 2: *Average Change in BPM* – It was found that there was no clear pattern to the change in BPM over the duration of experiment.