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The effect of an external auditory stimulus on postural stability of participants with cochlear implants

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THE EFFECT OF AN EXTERNAL AUDITORY STIMULUS ON POSTURAL STABILITY OF PARTICIPANTS WITH COCHLEAR IMPLANTS

by

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Abstract. Postural control was evaluated in cochlear implant participants with and without amplification under several auditory paradigms. Speed of sway was recorded in each condition by means of Computerized Dynamic Posturography. Results indicate that an external sound source significantly improves balance in patients with cochlear implants.

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Abbreviations

3-D	3-Dimensional
ABC	Activities-specific Balance Confidence Scale
ADRO	Adaptive Dynamic Range Optimization
ASC	Autosensitivity
BVL	Bilateral Vestibular Loss
CDP	Computerized Dynamic Posturography
cHIT	Clinical Head Impulse Test
CI	Cochlear Implant
COP	Center of Pressure
dB	Decibel
dBA	A-Weighted Decibel
DHI	Dizziness Handicap Inventory
Hz	Hertz
DVA	Dynamic Visual Acuity
HIT	Head Impulse Test
HL	Hearing Level
HSN	Head Shake Nystagmus
MVP	Multichannel Vestibular Prosthesis
NIH-NIDCD	National Institutes of Health-National Institute on Deafness and Other Communication Disorders
PTA	Pure Tone Average
qHIT	Quantitative Scleral Coil Head Impulse Test

SCC	Semicircular Canal
SD	Standard Deviation
SLM	Sound Level Meter
SOT	Sensory Organization Test
SPL	Sound Pressure Level
SPSS	Statistical Package for the Social Sciences
VEMP	Vestibular Evoked Myogenic Potential
VOR	Vestibulo-ocular Reflex

Introduction

Balance and postural stability are traditionally considered to be controlled by three main sensory modalities. Visual, proprioceptive and vestibular sensory information integrate to enable the body to maintain an upright stance with the body's center of pressure above a base support provided by the feet (Maurer, Mergner, & Peterka, 2006). The vestibular system contributes information regarding head acceleration which the central nervous system combines with visual system input to stabilize gaze during movement (Danilov, Tyler, Skinner, Hogle, & Bach-y-Rita, 2007). Proprioceptive input provides information of body motion relative to support from the musculoskeletal system (Maurer, Mergner, Bolha, & Hlavacka, 2000). When sensory information from one or all modalities is degraded or absent, balance becomes more unstable (Dozza, Horak, & Chiari, 2007). The extent to which the auditory system contributes to balance is still unclear.

Many people have vestibular impairment. According to the National Institutes of Health-National Institute on Deafness and Other Communication Disorders (NIH-NIDCD) at least 2 million Americans will experience chronic imbalance, and more than 90 million will seek medical attention for balance at least once in their lifetime (Wall III & Rauch, 2002-2003). Among older adults, balance dysfunction is exceedingly common. Agrawal et al. (2009) found that the overall prevalence of vestibular dysfunction leading to imbalance in the US population ages 40 years and older from 2001 to 2004 was 34.5%, corresponding to 69 million Americans.

Furthermore, research has demonstrated balance dysfunction that is comorbid with other causes of neural deafness. Hearing loss and imbalance occur together in the presence of a number of syndromes and otologic disorders. Among others, imbalance and hearing loss occur together in cases of Ménière's disease (Belinchon, Perez-Garrigues, & Tenias, 2011), multiple sclerosis (Grénman, 1985), certain viral infections (Bosatra, 1989), and vestibular schwannoma (Timmer, et al., 2011).

Cochlear implants are the typical rehabilitative solution for those with profound neural hearing loss. However, balance has been shown to be negatively affected by damage sustained during implantation (Brey, Facer, Trine, Lynn, Peterson, & Suman, 1995; Melvin, Della Santina, Carey, & Migliaccio, 2008; Migliaccio, Della Santina, Carey, Niparko, & Minor, 2005). Brey et al. (1995) found using bithermal caloric irrigations that 41% of 17 cochlear implant patients had a postoperative persistent peripheral unilateral weakness. Migliaccio et al. (2005) used the head impulse test (HIT) to measure a change in vestibular function after unilateral cochlear implantation in 11 participants. Each participant was tested pre- and post-operatively. Post-operative testing was performed with the external processor removed. Results showed that one participant of 11 presented with reduced vestibular function in the implanted ear post-surgery. Melvin et al. (2008) evaluated balance function pre- and post-operatively using a battery of vestibular assessment tests including, quantitative scleral coil head impulse test (qHIT), clinical head impulse test (cHIT), head shake nystagmus (HSN), bithermal caloric irrigation, vestibular evoked myogenic potential (VEMP), dynamic visual acuity (DVA), and the dizziness handicap inventory (DHI). They found similar results to those of Migliaccio et al. in that few participants were affected negatively by the surgical implantation. There were no changes seen in any participant for HSN, cHIT, and DVA. There was a negative impact seen in one participant for qHIT and bithermal caloric irrigation. VEMP testing revealed the most negative influence from surgical implantation resulting in five participants with significantly increased or absent thresholds present post-operatively. Interestingly, while four participants perceived an increase in self-described dizziness, three others actually perceived a decrease in symptoms. Together, these studies indicate the possibility, but not certainty, of some balance dysfunction following implantation but raise the possibility that implantation may actually improve balance in some people.

Surgical implantation may be the cause of post-operative dizziness; conversely, inappropriate stimulation of the vestibular system by electrical current from the cochlear implant (CI) could also be a cause (Coordes et al., 2012). Coordes et al. (2012) found while studying sound-induced vertigo after cochlear implantation that some patients experience an increase in vertigo post-operatively likely caused by co-stimulation of the saccule vestibular organ as measured by VEMP testing. A retrospective study was performed by administering a questionnaire to 104 post-surgical participants. Of those participants, 18% reported sound-induced vertigo that occurred after cochlear implantation.

While cochlear implants may have a negative effect on balance, it is possible that a cochlear implant (or two) may improve balance. Few studies have attempted to determine the association of auditory information to balance maintenance. Some have found negative associations indicating that audition may in fact destabilize the subject. Raper and Soames (1991) performed a study in which they investigated the influence of auditory information on postural stability. The authors used two types of auditory stimuli, a pure tone and background conversation, coming from different directions. They found that there was always a destabilizing effect in the presence of sound. This was not dependent on the type or direction of the auditory stimulus in any condition. Others have found contradictory associations noting a positive association between a static external sound source and balance. Easton et al. (1998) compared orientation and postural stability in sighted and visually-impaired subjects. Their results showed that sway, analyzed in terms of center of pressure, was reduced in both groups when two speakers provided auditory information for spatial orientation.

Clinically, imbalance has been addressed with different types of rehabilitative strategies. Among them is physical therapy (Hall, Heusel-Gillig, Tusa, & Herdman, 2010). The authors examined the effect of vestibular adaptation exercises, in addition to standard balance and gait training, in older adults who presented with dizziness and no documented vestibular deficit. These vestibular-specific exercises were designed to increase gaze stability. Results of the study showed a decrease in risk of falls as well as improved balance-related confidence and gait speed. While this exercise may be beneficial, this study only looked at its effect as short term benefit. Whether or not the exercises are effective in the long term rehabilitation of the patient is still unclear. Wolf et al. (2006) demonstrated that Tai Chi is one area of physical therapy that provides benefit to older adults who are at a high risk for falling. The authors showed an increase in gait speed and an increase in ability to perform functional tasks such as time to rise from a chair three times, time to complete a 360º turn, and time to reach to pick up an object from the floor more efficiently. While this research shows some benefit with Tai Chi, there is a limitation to the population it will reach. There are patients unable to perform the exercises involved in Tai Chi, such as those with musculoskeletal limitations.

Other research in rehabilitative strategies has evaluated the efficacy of a *substitution prosthesis* (Danilov, Tyler, Skinner, Hogle, & Bach-y-Rita, 2007; Dozza, Horak, & Chiari, 2007; Goebel et al., 2009; Wall III, 2010; Hegeman, Honegger, Kupper, & Allum, 2005; Wesley & Krueger, 2011) where a non-balance-related sensory channel is used. Danilov et al. (2007) used Computerized Dynamic Posturography (CDP) to measure improved postural control with the use of electrotactile stimulation of the tongue in participants with peripheral and central vestibular pathologies. Results demonstrated an improvement in composite Sensory Organization Test (SOT) scores and improved self-perceived ability to perform daily functional tasks as measured by the Dizziness Handicap Inventory (DHI) and The Activities-specific Balance Confidence Scale (ABC). Goebel et al. (2009) used CDP to measure improved postural control with the use of head-mounted vibrotactile stimulation in participants with bilateral vestibular loss (BVL). The authors found both a reduction in falls and improved time-to-fall scores on both conditions 5 (eyes closed, support surface sway-referenced) and 6 (eyes open, support surface and visual surround sway referenced) of the SOT with stimulation. Sway referencing refers to the movement of the platform; in that, it will only sway if the participant standing on it sways. Dozza et al. (2007) used a force plate to determine the efficacy of an external auditory signal varying in frequency and amplitude. The authors assessed the ability of the auditory signal to minimize tilt in the antero-posterior and lateral directions respectively on center of pressure (COP) displacement in profound BVL participants. Results of this study indicated the more severe the vestibular pathology, the more benefit the participant received. Also observed was that when participants were vision-dependent and vision was reduced, the participant received the most benefit. This result was seen for those who were somatosensory-dependent as well. If somatosensory information was reduced, the participant received the most benefit.

An alternative to substitution prostheses is *sensory augmentation*, where extra information from a balance-related sensory channel is provided. Wesley and Krueger (2011) used an eyewear mounted visual display in an attempt to decrease symptoms associated with motion intolerance. The authors examined the perceived effects in 25 participants with motion intolerance. Participants were to rate the “helpfulness” of the device in managing specific symptoms. Participants rated the device display as helpful for all symptoms assessed including nausea, vomiting, awareness of movement, general ill feeling, and cold “clammy” feeling. Participants were also asked how long a typical episode of motion intolerance lasted prior to use of the device display and with the use of the device display. Results of this study revealed a reduction in the duration of symptoms after an episode of motion intolerance with the use of the device display. Hegeman et al. (2005) performed a study in which they provided auditory feedback emitted from a speaker set to the right, left, front and rear of the participant. Feedback was provided when sway, measured from a force plate, was greater than a preset angle. The auditory feedback was in the form of a tone emitted from the direction of sway. The tone intensity increased with increasing sway angle. The authors found that people with bilateral vestibular loss were able to use an external sound source as auditory prosthetic biofeedback to maintain upright stance. This effect was seen to be most effective with lateral sway.

A *true sensory prosthesis* is implantable and will deliver sensory cues directly to the nervous system (Chiang, Fridman, Dai, Rahman, and Della Santina, 2011; Dai, Fridman, Davidovics, Chiang, Ahn, and Della Santina, 2011; Lewis et al. 2011). For example, cochlear implantation for hearing sends the auditory signal directly to the central auditory nervous system by way of the electric stimulation from the implanted electrode array. Chiang et al. (2011) developed a vestibular sensory prosthesis. It is an implantable device designed to sense head rotation by sampling 3-Dimensional (3-D) rotational velocity. To accomplish this, the device uses an angular rate sensor, gyroscope, and linear accelerometer. Dai et al. (2011) tested the 3-D vestibular sensation of this multichannel vestibular prosthesis (MVP) in five rhesus monkeys using vestibulo-ocular reflex (VOR). Each monkey received intratympanic gentamicin treatment bilaterally and implanted with the MVP device in the left ear only. The authors evaluated these rhesus monkeys under three different conditions: (1) prosthetic stimulation of a constant rate during passive whole-body rotations (baseline VOR); (2) pulse frequency-modulated prosthetic electrical stimulation with the monkey stationary (artificially-evoked VOR); and (3) prosthetic stimulation rate-modulated for each ampullary nerve during whole-body rotations (combined baseline and artificially-evoked VOR). They found that during sinusoidal rotation with rate-modulated stimulation, VOR gain was about four times larger than the VOR gain without modulated MVP input, yet still only half that of normal VOR gain. Therefore, the authors concluded that the MVP was able to partially restore VOR gain for head movements. This method of vestibular rehabilitation is still new and in the process of evaluation. Until this method is perfected and proven to be efficient in humans, researchers must still evaluate other rehabilitative strategies.

If audition contributes meaningfully to balance, it would be possible to develop a sensory augmentation device using an auditory stimulus as an *auditory field anchor*. If a person with imbalance is able to use a static external sound source to anchor his/her body in space, it has the potential to improve balance control. The purpose of the present study is to investigate the effect of a static external auditory stimulus on maintaining balance in adults with cochlear implants. The investigators believe that an external auditory sound source can be used by people with cochlear implants to create an auditory field anchor in their auditory environment.

Methods

Study Objectives

The aims of the current study were 1) to determine if an external auditory sound source improves postural control in cochlear implant users, 2) to determine if improvement in postural control depends on placement of the external sound sources with respect to the subject, and 3) to determine if improvement in balance with auditory stimulation is significant when compared to improvement due to visual input.

Participants

All participants gave informed consent prior to carrying out the experimental tasks (Washington University in St. Louis School of Medicine Human Research Protection Office Institutional Review Board Protocol. 201108022). All participants were recruited from Washington University's Cochlear Implant Division of the Department of Otolaryngology-Head and Neck Surgery. Participants were compensated for their time. The investigators performed a power analysis to determine sample size necessary based on unpublished data. Five male and eight female CI patients participated; the age of the participants was 52 ± 21 years (mean ± standard deviation). They were either bilateral CI users or bimodal CI and hearing aid users (3 bilateral, 10 bimodal; 8 Cochlear Americas, 5 Advanced Bionics). With the exception of one participant, aided CI pure tone averages (PTA) were 35 dB HL or better (PTA – mean = 23.1 ± 7.9 dB HL). Etiology of vestibular dysfunction and hearing loss varied among participants. See Tables 1 and 2 for specific participant information.

Measurement System

Testing was performed in Washington University in St. Louis School of Medicine's Dizziness and Balance Center using NeuroCom's EquiTest Computerized Dynamic

Posturography (CDP) platform. Readings from pressure sensors located at the four corners of the force platform were sampled at a rate of 100 Hz. For each trial, measurements were taken over 20 seconds. Center of pressure was calculated trigonometrically from the four pressure measurements.

Auditory Field System

Four speakers (SPKR-R1-BK-L02, GrandMax, Piscataway, New Jersey, frequency response 280-16,000 Hz) were mounted to the left, right, front, and rear of each participant and adjusted to ear level. Speakers could be controlled in pairs to allow four auditory conditions: silence, 4-speaker, left + right speakers on, front + back speakers on. For each participant the speakers were set to full volume without optional bass enrichment.

White noise generated using the wgn function in MATLAB (MathWorks, Natick, MA) was presented from Windows Media Player on a Dell Inspiron 1526 laptop computer wired to a four channel stereo amplifier with a frequency output range of 20-20,000 Hz (MicroAmp HA400, Behringer, Willich, Germany). White noise was used because it was not possible to obtain frequency specific aided thresholds of the aided ear to determine an audible level in bimodal users. White noise is composed of all frequencies and therefore would be audible by the bimodal amplification users no matter what the frequency region of hearing loss. The white noise was presented at a level of 55 dB SPL (re: 0.0002 dynes/cm^2). This minimum level was chosen to maintain that it was audible by each participant (see individual PTAs in Table 2).

Sound could not be presented at a higher level due to signal processing algorithms within the CI devices. Compression activates in both Cochlear Americas and Advanced Bionics devices when the level of background noise reaches an exact specified level. Once compression is activated, the level of the background noise decreases. The specific level that compression becomes active is dependent on each implant system and additional user settings. The use of 55 dB SPL (re: 0.0002 dynes/cm^2) was determined as a soft enough input level to ensure each device would not activate infinite compression for each type of CI system.

Participants were asked to place their devices in programs set for "quiet situations" in which compression would not be active. This was for added assurance that each device would not activate compression in the presence of the white noise. However, some participants were uncertain of the processing options provided to them in their devices and/or wore a hearing aid that automatically changed programs in the presence of background noise causing the compression applied to be unpredictable. Therefore, it was not possible to control for these compression characteristics.

The experimental enclosure was 1.07 meters on the intra-aural axis and 0.97 meters along the antero-posterior axis. The anterior wall of the enclosure was cambered outward by 0.20 meters at the midline. Subjects' malleoleus was centered above the axel of rotation of the footplates, which was located 0.30 meters anterior to the back of the enclosure. Ambient noise level within the testing environment was measured using a Larson Davis 831 Sound Level Meter (SLM). The sound level was calibrated for two speakers presenting the sound stimulus and four speakers presenting the sound stimulus using the same SLM. Figure 1 illustrates the level of the stimulus when four speakers were active (measured in dB SPL (re: 0.0002 dynes/cm^2) with respect to the level of the background noise (measured using dBA weighting) present in the testing environment.

Measured Tasks

Prior to initiating testing, each participant's subjective sense of balance was evaluated using two questions: "Do you think your balance is better or worse than before you received your cochlear implant?" and "Do you feel that you have better balance with your cochlear implant processor on or off?" Ten of the thirteen participants also completed the Activities-specific Balance Confidence Scale (ABC) (Powell & Myers, 1995). The ABC scale was administered to aid in determining each participant's perceived benefit from his/her amplification devices. Participants were asked to fill out the ABC scale rating each activity twice, once in relation to their level of confidence while wearing their amplification devices and once in relation to their level of confidence without the use of their amplification devices.

Participants performed three conditions of the Sensory Organization Test (SOT) (Chaudhry, Bukiet, Ji, Findley, 2011). These included conditions 1 (eyes open, fixed support, fixed surround), 2 (eyes closed, fixed support) and 5 (eyes closed, support surface sway-referenced). Condition 1 was chosen as a baseline for balance performance. Conditions 2 and 5 were chosen due to previous findings of balance improvement with audition in visually-impaired participants (Easton et al., 1998). Conditions 2 and 5 were also chosen to isolate each sensory modality. Condition 2 removes vision, and condition 5 removes both proprioception and vision. For each SOT condition, 7 auditory paradigms were performed (Table 3). They were pseudo-randomized to reduce the impact of unfamiliarity or learning bias, with no sequence of auditory paradigms duplicated among subjects.

Under the no-auditory input paradigm, the participant was asked to remove both amplification devices and no external sound was presented from any speaker. For bimodal users, the three unilateral amplification paradigms were performed with the participant's CI only. For bilateral CI users, the patient self-identified which implant was "preferred" and the other was removed. In every case, this was the earlier implanted side.

Each trial was performed according to the manufacturer's guidelines (NeuroCom, Clackamas, OR). Each participant was fitted with a safety harness prior to stepping onto the platform. Once on the platform, the harness was connected to two suspension straps attached to an overhead bar. The straps were adjusted to be loose enough to avoid restriction and/or a perception of artificial support, but tight enough to avoid injury. Each participant's feet were placed on the force plate according to the CDP instructions. Placement was determined by height of the participant. The medial malleolus of each foot was centered directly over the pivot pin and the lateral calcaneus placed on the short (height of 30-55 inches), medium (height of 56-65 inches), or tall (height of 66-80). The participants were to remove their shoes but were allowed to continue wearing their socks.

Each participant was provided with instructions for each SOT condition and informed of which speakers the sound would be emitted from during each auditory trial. They were instructed to remain with their hands at their sides. After four auditory trials were completed, each participant was allowed to rest as needed.

After completion of all trials, participants were asked to rank, from 1-3, each auditory paradigm (silent, unilateral, bilateral) with respect to their subjective impression of benefit on balance. One was ranked as the most perceived benefit; while three was ranked as the least amount of perceived benefit.

Data Analysis

To control for noise, MATLAB was used to fit a curve to the XY coordinates for the center of pressure obtained from each trial of the CDP measurements. The "fit" function was used with the "SmoothingSpline" option and lambda equal to 0.1 to provide suitable artifact reduction while minimizing data approximation. The instantaneous speed of motion (in cm/s) readings were calculated by using the smoothed XY coordinates. The instantaneous speed of motion for each condition and sound paradigm were concatenated giving 60 total seconds of speed of motion readings. The 95th percentile of speeds across all samples within the total dataset (6000 samples totally) for each SOT condition and sound paradigm was determined. The 95th percentile speed was chosen instead of the maximum speed because this point was relatively different between sound on and sound off conditions. Thus, this speed represented the maximal speed of the slowest 57 seconds of the 60 second total trial time. A change in balance was calculated by taking the difference between the 95th percentile speed of motion of each experimental paradigm (e.g. between the “sound on” and “sound off” paradigm).

Statistical analysis was carried out using Statistical Package for the Social Sciences (SPSS) 19.0 (IBM, Chicago, IL). The 95th percentile speeds for each sound paradigm were compared at each SOT condition performed using a Wilcoxon Rank Sum Test. Correlations were evaluated using Pearson’s *r* to assess the degree of improvement and its relation to reference speed.

Scores on the ABC Scale were correlated with self reported balance difficulties and with data gathered during testing. The perceived benefit of amplification was determined by taking the difference between average ratings of confidence levels on the ABC Scale with and without amplification. The correlation between observed and perceived benefit from the ABC Scale was also measured.

Results

A distribution of the speed of movement of the center of pressure observed in one participant during condition 2 with sound on (bilateral amplification and 4-speakers) and off is shown in Figure 2. The shape of the curve is clearly non-Gaussian, with a prominent difference in the number of high-value speeds between the two auditory conditions.

Mean subject speed of motion of center of pressure for all conditions are reported in Tables 4 and 5. The speed of motion values were compared using the silent condition and different sound on paradigms to determine if there was a significant difference. No significant difference was found among any of the sound paradigms. There was a maximum difference observed between condition 2 silent and condition 2 with bilateral amplification and 4-speakers (p=0.055). The mean speed of motion was lower in condition 2 for all sound on paradigms tested than condition 2 silent.

There was no significant difference between mean speeds of motion of bilateral and unilateral amplification or between sound on paradigms. In all but one sound on paradigm the mean speed of motion was lower with bilateral amplification than unilateral amplification.

Further analysis was performed on condition 2 with bilateral amplification and 4-speakers. This was the auditory paradigm that demonstrated the most improvement in mean speed of motion of all the sound paradigms as compared to silent. To examine the effect of poor balance on degree of improvement, the 95% speed of motion obtained in condition 2 silent was correlated with condition 2 with bilateral amplification and 4-speakers (Figure 3). These values demonstrated a significant linear correlation (Pearson's r=0.93, p<0.001).

As there was some speculation that a ceiling effect may have marginalized improvement in participants with lower speed of motion measurements, the change from condition 2 with bilateral amplification to condition 1 silent and 4-speakers was compared to the change from condition 2 silent to condition 1 silent (Figures 4 and 5). This allowed for a direct comparison of improvement in balance from the addition of auditory input or the addition of visual input. Improvement from the addition of either sensory input was strongly correlated with each other (Pearson's r=0.927, p<0.001). Linear regression was performed to determine the degree of improvement with the addition of auditory input relative to the degree of improvement with visual improvement. It was found that auditory input could compensate for 84% of the improvement seen with visual input, 95% CI [61-106%].

To assess the validity of the measure of balance chosen, the researchers compared participants' ABC scores (with amplification) to condition 1 with bilateral amplification and 4-speakers (Figure 6). The researchers chose this condition and paradigm because it most reflected everyday activity in which vision was not hindered and amplification was able to be used to aid balance. The measure chosen correlated significantly with these scores (Pearson's r=-0.828, p=0.003).

To further assess perceived benefit, the participants ranked the auditory paradigms (silent, unilateral, bilateral) according to the auditory environment in which they felt the most stable. Three of the 13 participants reported a perception of no difference in stability between auditory conditions. Ten of the 13 participants reported bilateral amplification as the most stabilizing auditory condition and silent the least stabilizing auditory condition. The unilateral auditory condition was rated as more stabilizing than silence, yet less stabilizing than the bilateral auditory condition.

Discussion

The data presented here show for the first time that auditory input from cochlear implants can provide a significant improvement in balance and equilibrium among patients with imbalance. This may have profound implications for cochlear implant candidacy as well as providing evidence for the role of multimodal integration of auditory stimuli with vestibular and proprioceptive inputs to improve balance. It may also provide evidence for incorporating audition into vestibular rehabilitation programs.

Objective Effect of Audition on Balance

The data show that an external sound source led to a decrease in the speed of COP during quiet stance in the dark among subjects overall, although the relatively wide spread of speeds in the silent condition prevented statistical significance from being achieved. In fact, some participants experienced great improvement with an external sound source while others showed little change. Further analysis showed that those with better balance without sound tended to experience minimal improvement with additional auditory input. A similar trend was noted when examining the improvement from condition 2 to condition 1. Not surprisingly, the degree of improvement from condition 2 to condition 1 was significantly correlated with the degree of improvement from condition 2 no sound to condition 2 bilateral amplification and all speakers on. Perhaps the participants without disequilibrium who did not improve with amplification are unable to perform any better. They reach a ceiling effect as their abilities plateau. This indicates a need for additional testing of healthy, normal participants under these same auditory paradigms to determine the level at which the participants should be able to perform.

Most subjects were unable to complete condition 5. Although condition 5 showed a decrease in number of falls when the sound was presented, the difference was not significant.

Perhaps an external sound source will improve balance only if one of the sensory systems that contribute to balance is compromised. This is evident by the results showing no significant improvement in condition 5 where both vision and proprioceptive inputs were compromised. Yet there was improvement in the same participants for condition 2 where vision only was compromised. To further illustrate this finding, further research would need to be performed assessing all SOT conditions in combination with an external sound source. This may suggest which compromised senses benefit the most from an external sound source.

Subjective Effect of Audition on Balance

The researchers found that participant perception of improvement did not always match the quantification of their improvement. If a participant perceived an improvement with amplification, and the data did not reflect this improvement, perhaps he/she was not particularly aware of the task. For those who perceived a benefit and none was seen in the data, some factor is providing them with this sense of improvement. It is possible that amplification provides deaf or hard of hearing people increased security within their environment and to move about within it. This may indicate that these participants could be taught to use sound to their benefit.

Most participants reported a perceived benefit of imbalance with amplification, particularly when both ears had access to the auditory stimulus in the bilateral/bimodal conditions as opposed to one in the unilateral conditions. However, the current data indicated that the difference in conditions only approached significance. This observed finding is in part due to the small sample size. The perceived benefit with bilateral access to sound was greatly preferred over unilateral access to sound. This is another indication that there is some perceptual benefit to cochlear implantation that is not quantifiable.

Measurement Technique

The mismatch between perceived and observed improvement could also be due to the metric chosen to analyze COP data. Perhaps the metric chosen was not the most relevant metric to show “improvement”, the researchers began analyzing the current data by examining the maximum amount of sway each participant exhibited during each condition. These data showed no statistical significance, which may indicate the authors’ measure is not sensitive enough to determine a difference with and without an external sound source or that it poorly correlates with balance perception. In addition, the researchers analyzed area of sway. They found this parameter to be an inappropriate measure of sway, finding that some participants shifted their positioning strategy in the midst of a trial resulting in a greater area of sway than would have otherwise. Also in analyzing area of sway, the researchers did not find it accurate to choose one trial from three for each condition. There was not an exact method of choosing each trial to analyze.

Literature evaluating the extent of postural control has used a number of parameters to analyze COP. Among those parameters are fractal dimensions (Cimolin, Galli, Rigoldi, Grugni, Vismara, Mainardi, & Capodaglio, 2011), frequency domains (Kapoula et al., 2011), antero-posterior sway (Zumbrunn, MacWilliams, & Johnson, 2011), mediolateral sway (Zumbrunn, MacWilliams, & Johnson, 2011), circular area of sway (Huang, Hsu, Kuan, & Chang, 2011), maximum excursion (Zumbrunn, MacWilliams, & Johnson, 2011), velocity (Lafond, Corriveau, He´bert, & Prince, 2004; Doyle, Newton, & Burnett, 2005), and acceleration (Kapoula et al., 2011). The current study analyzed speed of sway which has demonstrated a difference between sway with amplification and sway without amplification. These data also demonstrated a significant correlation with reported symptoms associated with imbalance validating this method of analysis.

The authors searched for a measure that was reliable in groups with less than perfect balance. It has been demonstrated that analyzing the mean speed of motion has a strong correlation compared to other measures commonly used to analyze COP especially with the shorter test intervals used in this study (Lafond, Corriveau, He´bert, & Prince, 2004). In the current study, however, greater interest was shown toward higher speed ranges to determine whether the sound stimulus would facilitate improved instability. In that selection of peak speed from trials produces unreliable results (Doyle, Newton, & Burnett, 2005). It was determined to use the 95th percentile to reduce analysis of erroneous data.

After analysis of speed of sway, significant positive correlations were seen when comparing condition 2 silent to condition 2 with bilateral amplification and 4-speakers. Other investigators have analyzed center of mass tracings, frequency domains, and fractal dimensions, results of the current study indicate significant differences with speed of motion. While the investigators of the current study found significant correlations using the 95th percentile speed of motion and validated these results with further correlation of the ABC Scale, further analysis of sway measuring additional metrics is necessary in order to find the most effective parameter. Finding the best parameter to analyze is important because researchers want to find the parameter that is the most sensitive. It is crucial to optimize the ability of CDP to provide relevant information regarding sway. If the most sensitive parameter is used, CDP will better be able to identify if an external sound source is capable of reflecting improved postural control.

Auditory Paradigm

Results of the current study did not show a statistically significant difference between postural control with two speakers (right and left, front and back) and four speakers (right, left, front, back) presenting the stimulus. There was, however, a slight increase in the 95th percentile speed of motion from bilateral amplification to unilateral amplification. This improvement was most likely due to the increased auditory localization abilities available when two ears are amplified as opposed to only one (Potts, Skinner, Litovsky, Strube, and Kuk, 2009). These results indicate that cochlear implants are a benefit to balance. It is possible that, at least in a considerable group of people, the very small risk of vestibular impairment (Melvin et al., 2008; Migliaccio et al., 2005) is outweighed by potential improvement. The lack of significance in these results is possibly due to the improvement occurring as a reflection of solely having the CI on and activated. However, the investigators did not perform a condition where the participant wore the CI and had no sound. It is not possible to determine that the improvement was due to the presence of an external sound source.

The current findings demonstrated that the presence of an external sound source provided benefit for stability to those with CIs which was almost as beneficial as the addition of vision under the same condition. For those who are visually-impaired and present with imbalance, these data present an argument for the integration of auditory sensation into potentially highly effective vestibular rehabilitation programs.

Limitations

Limitations of this study include the inability to know exactly how each participant’s hearing aid or implant was processing the signal as it was presented. It is possible that either of these devices enacted a noise reduction algorithm that reduced the intensity of the external sound source. This would potentially have affected the participant's ability to fully benefit from the external sound presented from each speaker. The authors were also unable to determine the hearing aid benefit with bimodal listeners. Limited benefit could have affected the participant's ability to hear the external sound at the same level as other participants. Only one participant reported an inability to hear the sound from all 4 speakers. This may have affected the participant's ability to use the left and right speaker paradigm to its full capacity. Lastly, the researchers did not perform an auditory condition where the participants wore their amplification devices and had no external sound. For this reason, one may not definitively conclude that the differences observed were due to the presence of the external sound source.

The current study recruited participants of all ages. The researchers did not analyze the results of younger participants compared to older participants due to the small sample size and wide range of ages. This results in a need for further research to determine the effect of earlier implantation versus implantation later in life.

Conclusions

The present study showed significant positive correlations between the 95th percentile speeds of sound on and silent auditory paradigms performed. This correlation was the most significant when evaluating condition 2 performed with bilateral amplification and 4 speakers compared to condition 2 silent. This result demonstrated that those with poor balance benefit more from the auditory sound source than those with better balance. Additional results indicated a significant positive correlation of auditory and visual sensory modalities and their effect on balance. These results demonstrated that patients with both visual and auditory deficits would benefit from either auditory or visual sensory input almost equally. Perceptual data obtained established a perceived benefit of increased stability with amplification rather than silent condition. This indicates that there is a psychological component to the perception of improved stability that is not quantifiable. Future research should further investigate these auditory paradigms evaluating specific patient populations as well as the multiple metrics used to analyze COP data.

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Table 1. Participant Characteristics

Participant	Gender	Age	Etiology of Hearing Loss	Etiology of Vestibular Loss	Years with Imbalance (Less than one year - Greater than 5 years)
1	Male	19	Cytomegalovirus	Peripheral Dysfunction	Greater than 5 years
2	Male	40	Idiopathic	Peripheral Dysfunction	Less than 1 year
3	Male	59	Charcot-Marie Tooth Syndrome	Charcot-Marie-Tooth Syndrome	Greater than 5 years
4	Female	71	Meniere's Disease	Meniere's Disease	Greater than 5 years
5	Female	59	Idiopathic	No known loss	No Imbalance
6	Female	17	Idiopathic	Vestibular Migraine	Greater than 5 years
7	Female	45	Idiopathic	No known loss	No Imbalance
8	Female	64	Idiopathic	Idiopathic	Greater than 5 years
9	Female	80	Idiopathic	No known loss	No Imbalance
10	Female	27	Cytomegalovirus	Idiopathic	Less than 1 year
11	Female	64	Sudden Idiopathic	Idiopathic	Greater than 5 years
12	Male	75	Presbycusis	No known loss	No Imbalance
13	Male	54	Cogan Syndrome	No known loss	No Imbalance

Table 2. Particpant CI Characteristics

Participant	Mode of Amplification	Ear of Implantation	Brand of Implant	Implant	Processor	Length of Time with Implant	CI Aided PTA (500, 1k, 2kHz) (dB HL)
1	Bilateral	Left/Right	Advanced Bionics	Right (1st): Clarion Left (2nd): HiFocus1J	Right: Platinum Left: Harmony	Right: 13 years Left: 5 years	Right: 26 Left: 30
2	Bimodal	Right	Cochlear Americas	Freedom Contour	CP810	5 months	Right: 14
3	Bimodal	Right	Advanced Bionics	HiFocus1J	Harmony	4 years	Right: 16
4	Bimodal	Right	Cochlear Americas	Nucleus 5	CP810	6 months	Right: 16
5	Bilateral	Left/Right	Cochlear Americas	Right (2nd): Nucleus 5 Left (1st): Nucleus 24	Right: CP810 Left: CP810	Right: 2 years Left: 8 years	Right: 22 Left: 22
6	Bilateral	Left/Right	Advanced Bionics	Right (2nd): HiFocus1J Left (1st): Clarion	Right: Harmony Left: Harmony	Right: 8 years Left: 15 years	Right: 31 Left: 41
7	Bimodal	Right	Cochlear Americas	Nucleus 5	CP810	1 year 6 months	Right: 25
8	Bimodal	Left	Advanced Bionics	HiFocus1J	Harmony	4 years	Left: 29
9	Bimodal	Right	Cochlear Americas	Freedom Contour	CP810	9 years	Right: 33
10	Bimodal	Right	Cochlear Americas	Nucleus 5	CP810	10 months	Right: 18
11	Bimodal	Right	Cochlear Americas	Freedom Contour	CP810	4 months	Right: 16
12	Bimodal	Right	Cochlear Americas	Freedom Contour	CP810	7 months	Right: 15
13	Bimodal	Right	Cochlear Americas	Nucleus 24	Freedom	9 years	Right: 16

Table 3. Seven Auditory Paradigms

Mode of Amplification	Sound Source Paradigm
None	None
Unilateral	Left and Right
Unilateral	Front and Rear
Unilateral	All
Bilateral/Bimodal	Left and Right
Bilateral/Bimodal	Front and Rear
Bilateral/Bimodal	All

Table 4. Mean Speed of Motion for Sound Paradigms in Condition 1

	Sound Off	Sound On Bilateral			Sound On Unilateral		
	Off	**All**	**Front-Back**	**Right-Left**	**All**	**Front-Back**	**Right-Left**
Mean	2.78	2.52	2.37	2.29	2.87	2.83	2.48
N	13	13	13	13	13	13	13
Standard Deviation	0.96	1.08	0.93	0.93	2.36	2.04	1.20
Minimum	1.34	1.24	1.06	1.05	1.29	1.16	1.41
Maximum	3.98	5.47	4.34	4.78	10.38	9.26	5.99

Table 5. Mean Speed of Motion for Sound Paradigms in Condition 2

	Sound Off	Sound On Bilateral			Sound On Unilateral		
	Off	**All**	**Front-Back**	**Right-Left**	**All**	**Front-Back**	**Right-Left**
Mean	5.18	3.66	4.15	4.26	4.63	4.40	4.16
N	13	13	13	13	13	13	13
Standard Deviation	4.02	1.53	2.10	2.47	3.45	2.26	1.99
Minimum	1.67	1.34	1.47	1.83	1.45	1.56	1.70
Maximum	16.35	6.77	8.38	10.47	13.86	9.26	8.15

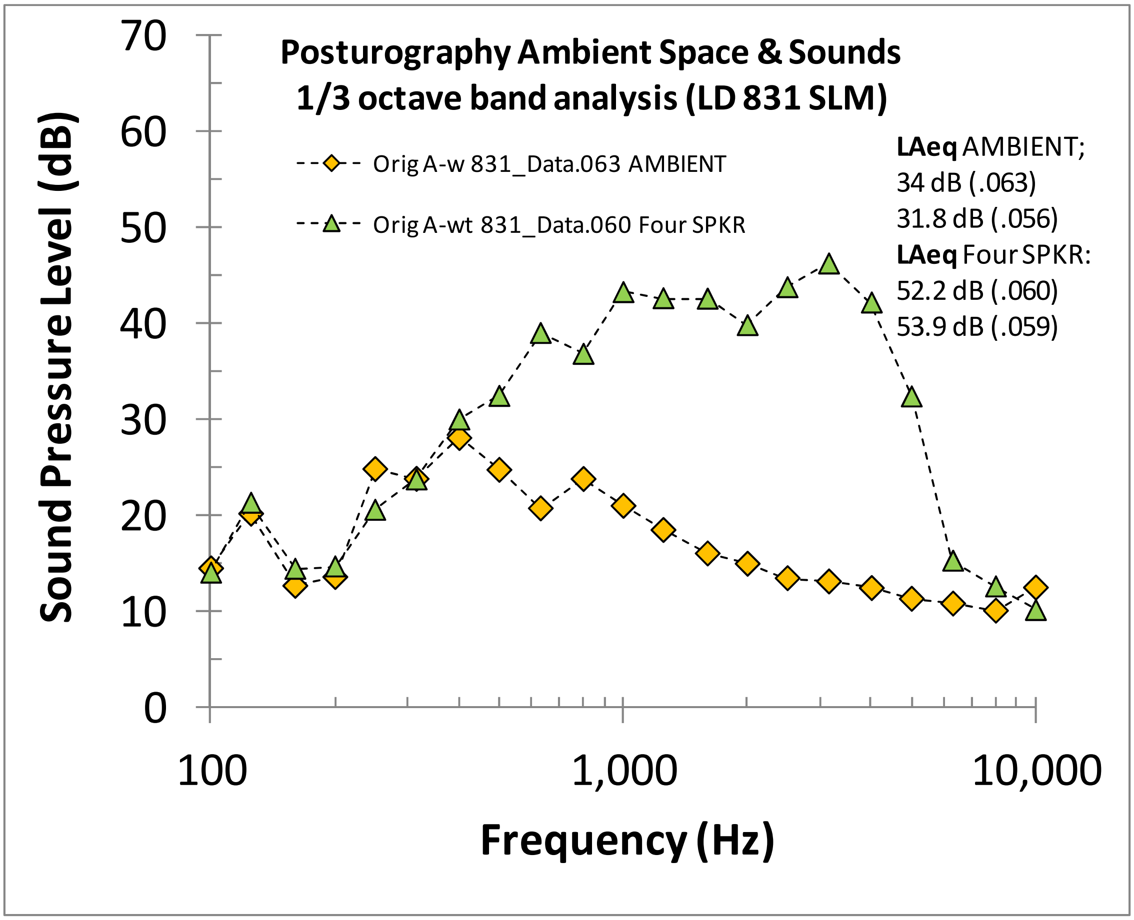

Figure 1: Stimulus level when four speakers were active (measured in dB SPL (re: 0.0002 dynes/cm^2) with respect to the level of the background noise (measured using dBA weighting) present in the testing environment.

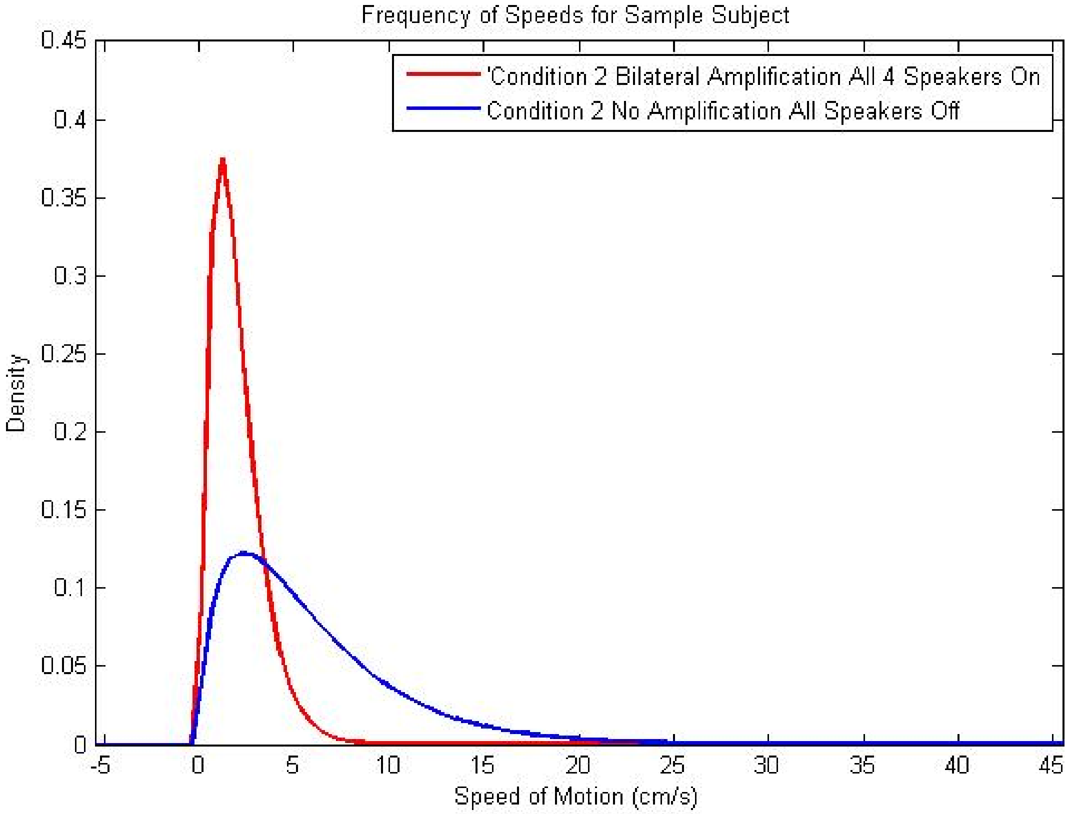

Figure 2: The distribution of the speed of movement of the center of pressure observed in one participant during condition 2 with sound on (bilateral amplification and 4-speakers) and off (silent).

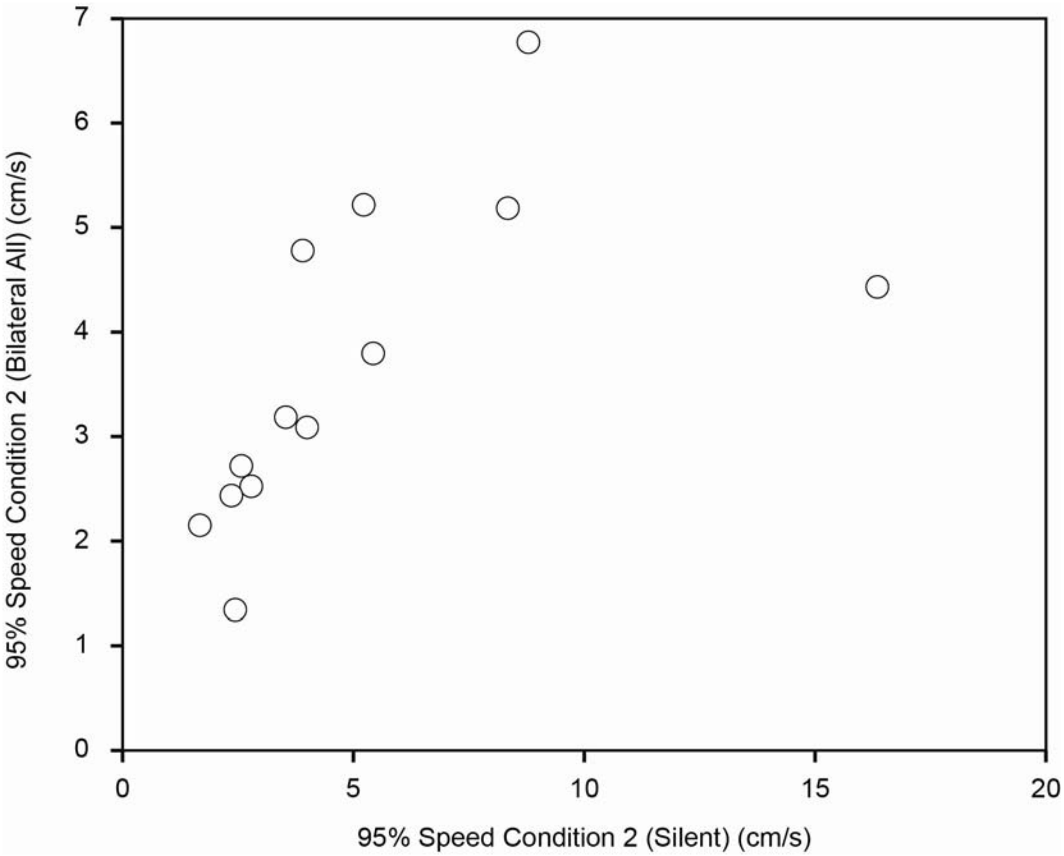

Figure 3: Correlation of the 95% speed of motion of condition 2 silent compared to condition 2 with bilateral amplification and 4-speakers.

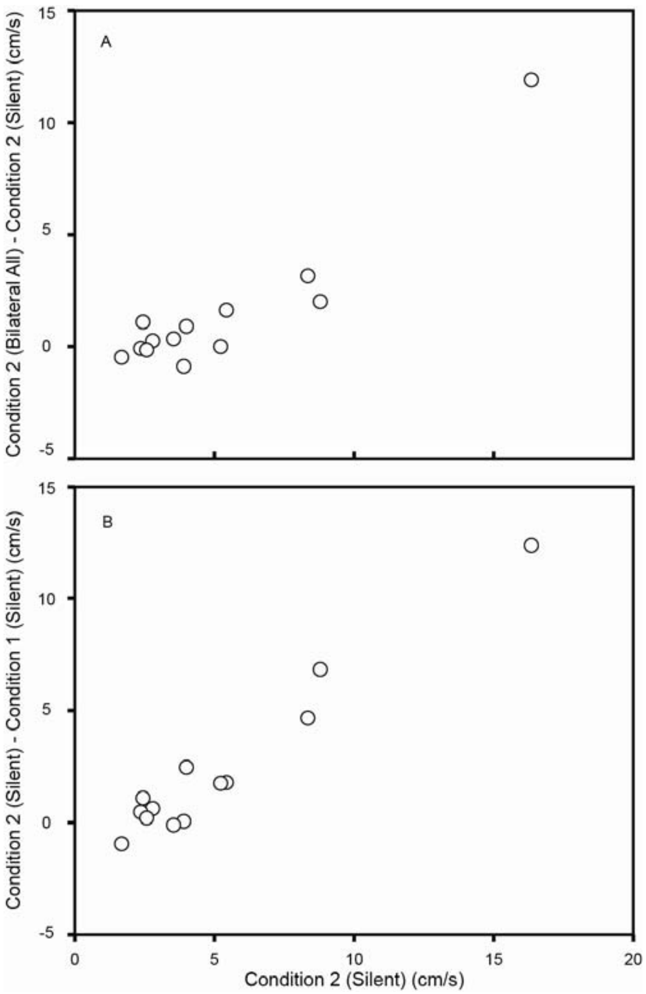

Figure 4: Correlations of auditory and visual sensory input. (A) Correlation of the change in speed of motion from condition 2 with bilateral amplification and 4-speakers to condition 2 silent versus condition 2 silent speed of motion. (B) Correlation of the change in speed of motion from condition 2 silent to condition 1 silent versus condition 2 silent.

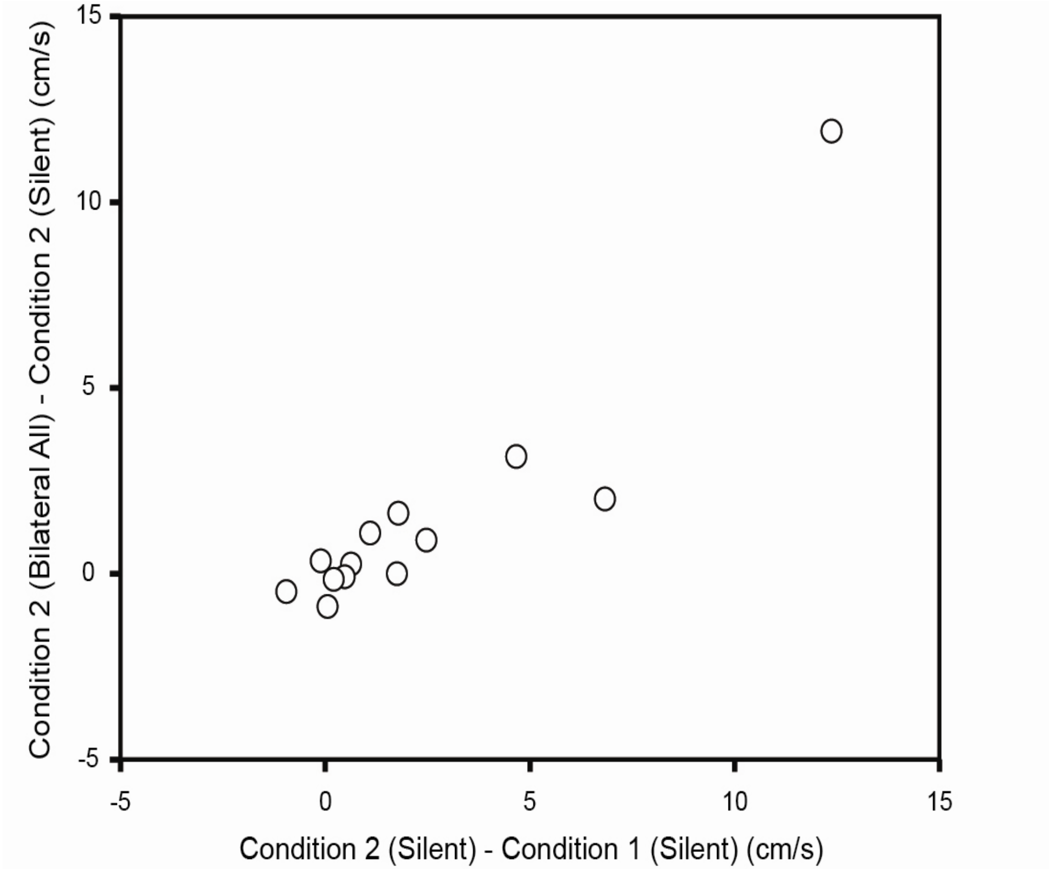

Figure 5: Correlation of the change in speed of motion from condition 2 with bilateral amplification and 4-speakers to condition 2 silent versus the change in speed of motion from condition 2 silent to condition 1 silent.

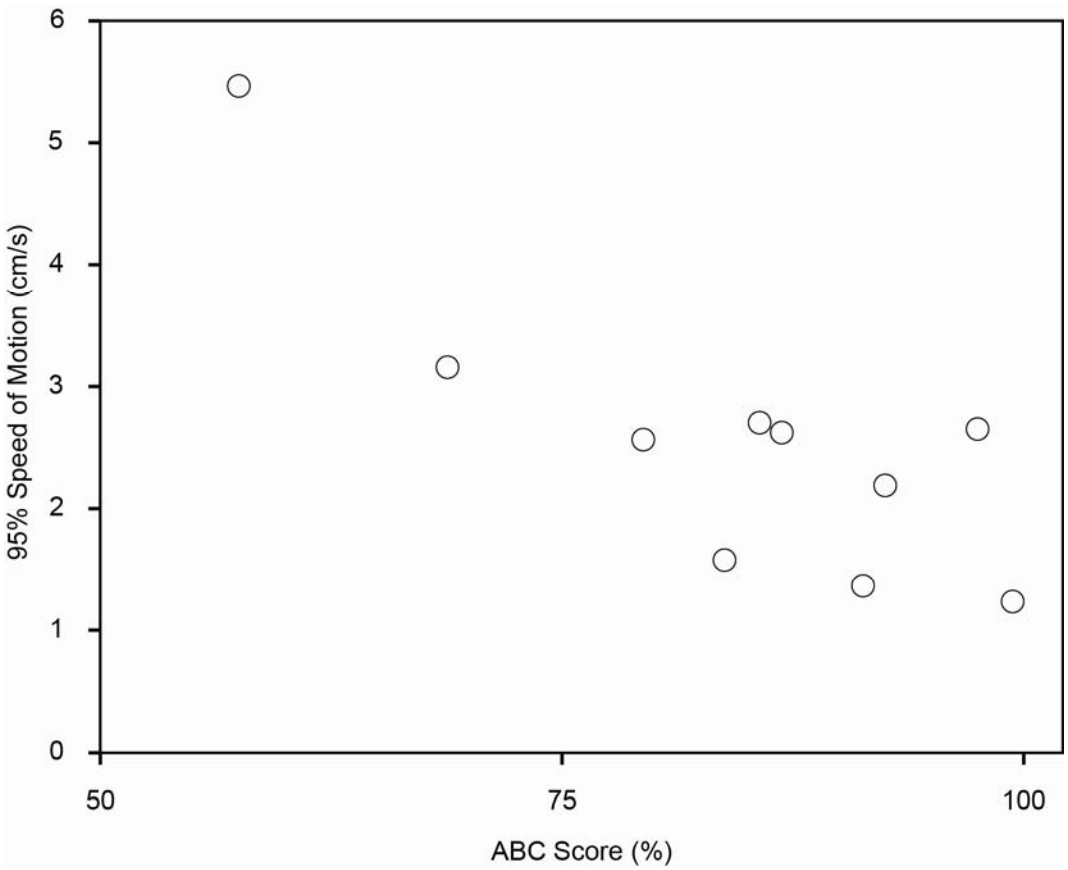

Figure 6: Correlation between participants' ABC scores (with amplification) and condition 1 with bilateral amplification and 4-speakers.

Appendix

The Activities-specific Balance Confidence (ABC) Scale*

Instructions to Participants:
For each of the following, please indicate your level of confidence in doing the activity without losing your balance or becoming unsteady from choosing one of the percentage points on the scale form 0% to 100%. If you do not currently do the activity in question, try and imagine how confident you would be if you had to do the activity. If you normally use a walking aid to do the activity or hold onto someone, rate your confidence as it you were using these supports. If you have any questions about answering any of these items, please ask the administrator.

The Activities-specific Balance Confidence (ABC) Scale*

For each of the following activities, please indicate your level of self-confidence by choosing a corresponding number from the following rating scale:

0% 10 20 30 40 50 60 70 80 90 100%
no confidence completely confident

"How confident are you that you will not lose your balance or become unsteady when you…

1. …walk around the house? ____%
2. …walk up or down stairs? ____%
3. …bend over and pick up a slipper from the front of a closet floor ____%
4. …reach for a small can off a shelf at eye level? ____%
5. …stand on your tiptoes and reach for something above your head? ____%
6. …stand on a chair and reach for something? ____%
7. …sweep the floor? ____%
8. …walk outside the house to a car parked in the driveway? ____%
9. …get into or out of a car? ____%
10. …walk across a parking lot to the mall? ____%
11. …walk up or down a ramp? ____%
12. …walk in a crowded mall where people rapidly walk past you? ____%
13. …are bumped into by people as you walk through the mall?____%
14. … step onto or off an escalator while you are holding onto a railing? ____%
15. … step onto or off an escalator while holding onto parcels such that you cannot hold onto the railing? ____%
16. …walk outside on icy sidewalks? ____%

*Powell, LE & Myers AM. The Activities-specific Balance Confidence (ABC) Scale. *J Gerontol Med Sci* 1995; 50(1): M28-34