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RESEARCH ARTICLE

Auditory white noise reduces postural fluctuations even in the absence of vision

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Abstract The contributions of somatosensory, vestibular, and visual feedback to balance control are well documented, but the influence of auditory information, especially acoustic noise, on balance is less clear. Because somatosensory noise has been shown to reduce postural sway, we hypothesized that noise from the auditory modality might have a similar effect. Given that the nervous system uses noise to optimize signal transfer, adding mechanical or auditory noise should lead to increased feedback about sensory frames of reference used in balance control. In the present experiment, postural sway was analyzed in healthy young adults where they were presented with continuous white noise, in the presence and absence of visual information. Our results show reduced postural sway variability (as indexed by the body's center of pressure) in the presence of auditory noise, even when visual information was not present. Nonlinear time series analysis revealed that auditory noise has an additive effect, independent of vision, on postural stability. Further analysis revealed that auditory noise reduced postural sway variability in both low- and high-frequency regimes (> or <0.3 Hz) of sway, suggesting that both spontaneous and feedback-driven aspects of postural fluctuations were influenced by acoustic noise. Our results support the idea that auditory white noise reduces postural sway, suggesting that auditory noise might be used for therapeutic and rehabilitation purposes in older individuals and those with balance disorders.

Keywords Postural sway · White noise · Visual feedback · Auditory feedback

Introduction

Postural stability relies on active motor adjustment and control of a distributed system of muscles (Balasubramaniam and Wing 2002). Successful control relies on prediction and feedback from the somatosensory, vestibular, and visual modalities (Dozza et al. 2007). Postural sway is sensitive to subtle changes in feedback (Yeh et al. 2010), and increased availability of information from these systems has been shown to improve balance, as in the case of light touch (Jeka et al. 1997; Wing et al. 2011). Although multisensory feedback is essential for postural control, individuals differentially depend on combinations of somatosensory, vestibular, and visual feedback for postural stability. The dominant dependence can change with circumstance, including impairment of one or more of the senses (Dozza et al. 2007; Hegeman et al. 2005). Partial compensation occurs in these systems to ensure balance not only for major impairment, but also for temporary interruptions, such as when we close our eyes. In this situation, sway variability increases, but balance can be maintained. Postural stability is greatest for healthy, young people who have intact somatosensory, vestibular and visual function, and strong multisensory compensation (Juntunen et al. 1987; Tanaka et al. 2001).

The mechanisms for postural control include two components that work on different timescales (Yeh et al. 2010). Lower frequencies in postural sway reflect feedback-based corrective processes, and higher frequencies reflect open-loop and exploratory processes (Yeh et al. 2014). Postural sway frequency spectra do not show two distinct ranges of

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higher power, but changes in feedback have been shown to influence the two frequency components differentially (Yeh et al. 2010), and the best-fit cutoff frequency between the two timescales is estimated to be 0.3 Hz (van den Heuvel et al. 2009). In a study that explored the relationship between the velocity of sway and the velocity of subthreshold vibrating somatosensory references during light touch, they found that head and body sway coupled to the oscillating reference, and that coupling was nearly in-phase to frequencies of 0.2 Hz and lower, and had a significant lag for higher frequencies. This supports that lower-frequency sway relies more on feedback than higher-frequency sway when there is a cutoff frequency of slightly over 0.2 Hz (Jeka et al. 1997).

Auditory feedback has been shown to influence postural sway, but is less documented than other modalities of feedback. Impairment of vision, proprioception, or vestibular systems leads to more reliance on audition (Dozza et al. 2007; Hegeman et al. 2005; Palm et al. 2009), and hearing loss has been shown to increase variability in postural sway, although the explanation for this is unclear. Juntunen et al. (1987) proposed that subclinical damage to the vestibular system with noise-induced hearing loss could explain the effect on stability, but there is no corroboration for vestibular damage in their participants because of the difficulty in examining damage too subtle for current clinical detection. Imbalance and hearing loss co-occur in a number of disorders, including Ménière's disease, multiple sclerosis, viral infections, and vestibular schwannoma (Mangiore 2012). Reduction in sway with auditory feedback has also been shown in people without visual, proprioceptive, or vestibular deficits (Dozza et al. 2007); audition might be utilized for postural stability even in people without impairment of other perceptual systems.

The aspect of auditory feedback that is most influential for balance is unknown. Attempts to encode position and velocity information in auditory feedback have resulted in mixed and confusing results. Hegeman et al. (2005) found very small improvements in stability with sound that provided information about position, but only when participants had their eyes open and were standing on a hard surface; they found no effect when participants' eyes were closed, when participants were standing on a foam surface designed to reduce somatosensory feedback from the feet, or when the sound provided velocity information. In contrast, Dozza et al. (2007) found a reduction in sway when the sound provided information about position, but only when participants' eyes were closed and participants were standing on a foam surface. They also found a lot of intersubject variability, possibly indicating that participants were responding to the feedback in individualized ways (Dozza et al. 2007). It is possible that the acoustic properties of the auditory stimuli might be more influential in reducing sway than any position or velocity information encoded in the stimuli. Auditory stimuli with changing acoustic properties, as in Hegeman et al. (2005) and Dozza et al. (2007), could result in mixed and inconsistent effects on sway if the acoustic properties themselves influence sway. Palm et al. (2009) found no effect on sway with music from a fixed location. Deviterne et al. (2005) found reduced sway when participants listened to speech, but not when they listened to a single sustained tone. Acoustic properties of the sound stimuli might be more influential than the sound-producing event, and informational feedback that event provides about how stable the stance is. The major differences between stimuli with changing acoustic properties and white noise are that noise is a complex sound, with many frequencies occurring at the same time, and noise can be presented continuously with acoustic properties that are held constant over the course of the experiment.

Noise in the somatosensory modality has been shown to reduce sway variability. Subsensory mechanical noise chips applied to the soles of the feet have been shown to reduce postural sway in healthy aging adults, adults with sensorimotor deficits of central and peripheral causes (Priplata et al. 2003, 2006), and in healthy young adults (Priplata et al. 2002). This shows that the presence of mechanical noise can reduce sway variability, which is thought to be a result of stochastic resonance (SR). SR describes the amplification of signals when adding noise to a threshold-based system, such as the nervous system. Subsensory mechanical noise was shown to increase sensory feedback from the feet. Because somatosensory noise improves postural sway (Priplata et al. 2002, 2003, 2006), we hypothesized that auditory noise would also improve postural sway, due to a similar SR mechanism. There is evidence that auditory noise from a fixed location can improve postural stability in patients with cochlear implants, and that this could be due to the sound serving as an auditory field anchor (Mangiore 2012). In the current experiment, postural sway was analyzed in healthy young adults without somatosensory, vestibular, visual, or auditory deficits during silence and sustained white noise. Participants were examined with their eyes open and closed. It was hypothesized that sway variability would be reduced with exposure to auditory white noise, and that this effect would be greater in the eyes-open condition than the eyes-closed condition because of the reliance on multisensory feedback for postural stability.

Methods

Participants

Nineteen healthy participants (7 men, 12 women; aged 18–25) of similar height (64.8 ± 4.2 inches) and weight

(146.5 ± 36.7 lbs.) were recruited from the University of California, Merced, undergraduate and graduate student populations. Participants with hearing loss, neurological disorder, arthritis, orthopedic conditions, recent injury, and/or balance disorders were not included in the study. The protocol was approved by the Institutional Review Board, and participants gave informed written consent prior to the experiment.

Experimental protocol

Participants were asked to stand on a force platform in a relaxed, comfortable standing position with their arms at their sides while wearing headphones. The headphones worn were designed to reduce noise from any other external source. Participants were instructed to keep their eyes on a black crosshair stimulus posted on the wall 229.0 cm in front of them at approximately eye level for the eyes-open trials and to keep their head facing forward and their eyes closed for the eyes-closed trials. Noise and silence conditions were presented in a randomized order. Trails lasted 30 s and were either accompanied by auditory white noise (10 trials at 75 dB) or silence (10 trials). Postural sway data were collected in a single session with 20 30-second trials of the four conditions (five trials each with eyes closed during silence, eyes open during silence, eyes closed during noise, eyes open during noise). The noise stimulus was generated using MATLAB to be a random signal with a constant spectral density. Participants were exposed to the noise stimulus prior to the experiment to verify that the noise stimulus was not uncomfortable for them.

CoP acquisition and analysis

Center of pressure (CoP) was sampled at 2000 Hz with an AMTI Force and Motion force platform (Optima BP400600-2000). The first 4 s of each trial was removed to eliminate any potential startle response the participants might have had to the stimulus onset. Radial sway (r) of the CoP was calculated for each time step (i) using anterior–posterior (x) and medial–lateral (y) components of sway following $r_i = \sqrt{x_i^2 + y_i^2}$. Average radial sway was calculated for each trial and was used to assess standing stability during the trials (Lafond et al. 2004a, b). Detrended fluctuation analysis (DFA) and recurrence quantification analysis (RQA) were used to quantify the sway patterns over time. The data were down-sampled for these analyses to 50 Hz. RQA measures used were percent determinism, percent recurrence, and entropy (delay = 40, embedding dimension = 4, radius = 10), and the standard largest box size was used (Richardson et al. 2007). Radial sway in low- and high-frequency ranges was examined separately to assess changes in slow and fast timescales of postural control (Yeh et al. 2010, 2014; van den Heuvel et al. 2009). Filtering was performed using a dual-pass, second-order Butterworth filter with a cutoff frequency of 0.3 Hz. The filter cutoff was chosen based on van den Heuvel et al. 2009. We used low- and high-pass Butterworth filtering routines, as in Yeh et al. 2010 and Yeh et al. 2014, to decompose sway into low (<0.3 Hz)- and high (>0.3 Hz)-frequency sway.

Results

Analysis of variability

Postural sway variability was reduced with the addition of auditory noise, and wandering behavior in both medial–lateral and anterior–posterior directions was reduced. The sway paths from representative trials from each condition for one subject are shown in Fig. 1.

Radial sway variability was compared using a two-way analysis of variance (ANOVA) EYES (closed vs. open) × 2 NOISE (no noise vs. noise) with repeated measures on the visual and auditory feedback conditions. We found a main effect of vision [$F(1,18) = 9.472$, $p = .006$] and noise [$F(1,18) = 6.873$, $p = .017$], as shown in Fig. 2. These results support that variability in postural sway decreases when eyes are open and with the addition of noise, contributing to more stability in standing balance. We also found a vision × noise interaction [$F(1,18) = 5.885$, $p = .026$], which supports that visual and auditory feedback contributes interactively to sway variability.

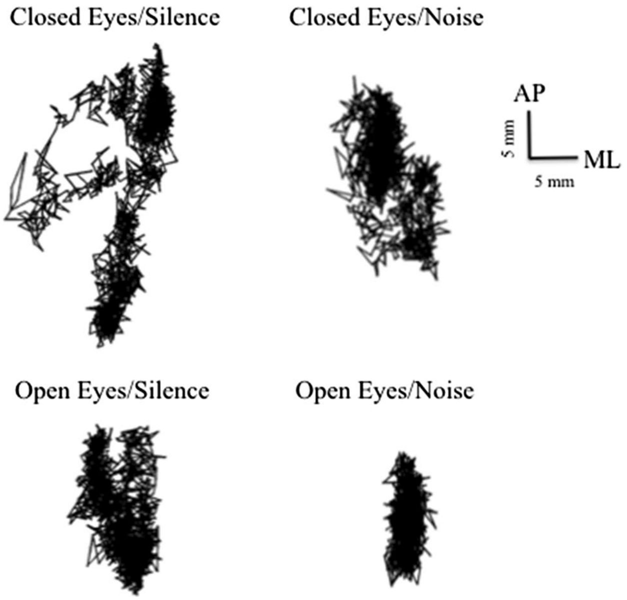

Fig. 1 Center of pressure displacement exhibited by one subject in eyes-closed/eyes-open and silent/noise conditions

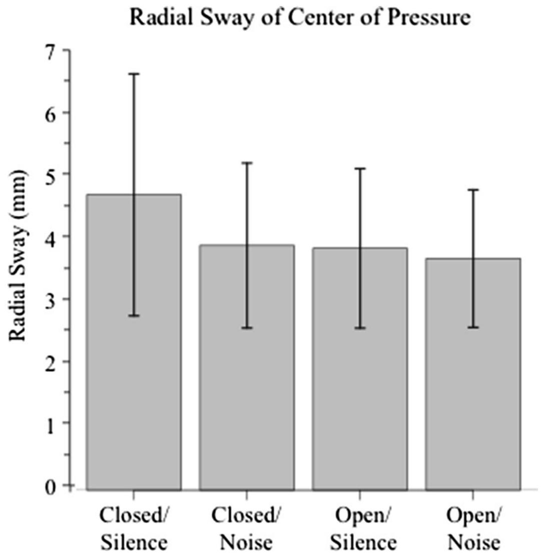

Fig. 2 Radial sway variability in eyes-closed/eyes-open and silent/noise conditions. *Error bars* represent ±1 standard deviation from the mean

Nonlinear analyses

Detrended fluctuation analysis revealed that the sway patterns exhibit antipersistent fBm ($1 < \beta < 1.5$), which is consistent with previous work on postural sway (Blázquez et al. 2010; Delignières et al. 2003). This means the sway moves in successive steps in random directions (a semi-random walk) and does not tend toward the same direction. This was the pattern in all four experimental conditions. There were no effects of eyes [$F(1,93) = .039$, $p = .844$], noise [$F(1,93) < .0001$, $p = .990$], or an interaction between them [$F(1,93) = 1.118$, $p = .293$]. Neither vision nor noise changed this random walk pattern typical of postural sway.

Recurrence quantification analysis was used to quantify the complexity of the sway over the last 26 s of each trial. The parameters we examined were percent determinism, percent recurrence, and entropy (Marwan et al. 2007). Each RQA parameter was compared across conditions using a two-way analysis of variance (ANOVA) EYES (closed vs. open) × 2 NOISE (no noise vs. noise) with repeated measures. As shown in Fig. 3a, percent determinism decreased when eyes were open and when noise was present. There was a main effect of eyes [$F(1,92) = 9.400$, $p = .003$] and noise [$F(1,92) = 4.112$, $p = .045$]. Having eyes open and hearing noise reduces determinism of radial sway movements. There was no eyes × noise interaction [$F(1,92) = 1.080$, $p = .301$], indicating that noise has an additive effect on the random nature of postural sway. As shown in Fig. 3b, percent recurrence decreases in the noise conditions. There was a main effect of noise [$F(1,93) = 4.806$, $p = .031$], but no effect of eyes [$F(1,93) = .249$, $p = .619$]. There was no eyes × noise interaction [$F(1,93) = .426$, $p = .516$]. As shown in Fig. 3c, entropy decreased when eyes were open and when noise was present. There was a main effect of eyes [$F(1,93) = 6.314$, $p = .014$] and noise [$F(1,93) = 7.813$, $p = .006$]. There was no eyes × noise interaction [$F(1,93) = 1.413$, $p = .238$].

Variability in high- and low-frequency ranges

In low-frequency sway (<0.3 Hz), there was a main effect of vision [$F(1,92) = 7.082$, $p = .009$] and noise [$F(1,92) = 6.539$, $p = .012$]. Both vision and noise reduced radial sway variability in the low-frequency band, as summarized in Fig. 4. The vision × noise interaction was also significant [$F(1,92) = 9.375$, $p = .003$], indicating that visual and auditory feedback interactively influenced feedback-based postural control mechanisms. In high-frequency

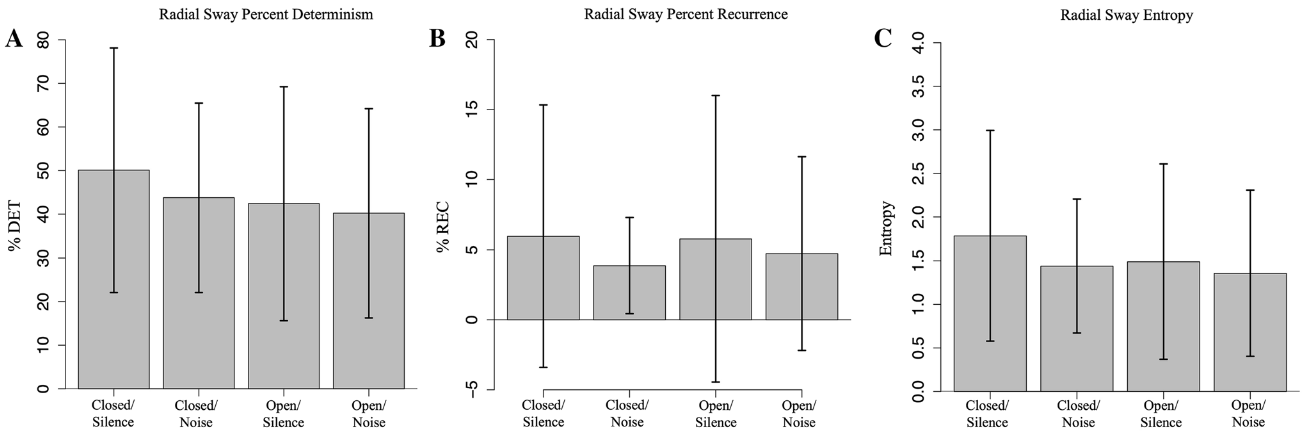

Fig. 3 Nonlinear measures of sway in eyes-closed/eyes-open and silent/noise conditions. *Error bars* represent ±1 standard deviation from the mean

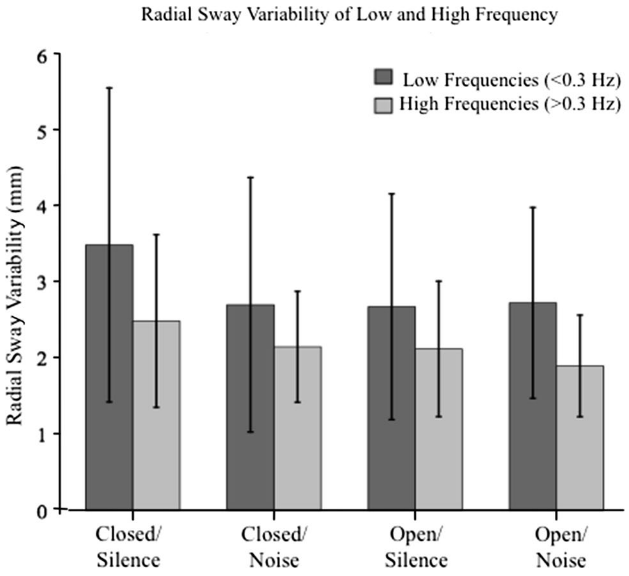

Fig. 4 Radial sway variability in low and high frequencies in eyes-closed/eyes-open and silent/noise conditions. *Error bars* represent ±1 standard deviation from the mean

sway (>0.3 Hz), there was a main effect of vision [$F(1,92) = 37.992$, $p < .001$] and noise [$F(1,92) = 19.558$, $p < .001$]. Vision and noise reduced radial sway variability in the high-frequency band, as shown in Fig. 4. There was no interaction between vision × noise [$F(1,92) = .919$, $p = .340$], indicating that visual and auditory feedback independently influenced exploratory postural control mechanisms. In low-frequency sway, noise interacts with vision, but in high-frequency sway, the effect of noise is additive.

Discussion

We show improved postural stability with auditory noise in healthy young adults using headphones. However, it is important to note that somatosensory noise presented to participants in the previous experiments was subthreshold, in that it was not actively detected by the participants. In our experiment, the auditory noise presented to participants was well within audible range (75 dB). The presented results support the idea that variability in postural sway decreases when eyes are open and with the addition of noise, contributing to more stability in standing balance. All postural sway exhibits antipersistent fractional Brownian motion, but the patterns of complexity are influenced by visual and auditory stimulation. Having eyes open and hearing noise reduces determinism of radial sway movements, and the effect of noise is additive. Percent recurrence decreases with noise, and entropy decreases with vision and noise independently.

One explanation for the noise effect on postural sway is that the sound provides an orienting reference when it comes from a fixed location (Zhong and Yost 2013). This is an argument that has also been used with regard to light touch. Somatosensory contact with an object provides the participant with a sensory reference frame that helps them stabilize their posture. Although acoustic noise can provide information about directionality, it is unlikely that it provides information about a sensory reference frame in the same way that light touch does. Also, with light touch, somatosensory contact with a moving object can also reduce sway variability (Jeka et al. 1997; Wing et al. 2011). It seems to be that increasing somatosensory feedback, whether the source is stationary or not, improves balance. Similarly, auditory stimulation from stationary and moving sources has been shown to reduce sway variability (Deviterne et al. 2005).

It is not the case that sound source does not matter in postural sway, but that it is not necessarily the driving force behind the noise effect. Pure tone and conversation from a fixed source on one side of the body during an eyes-closed condition actually has a destabilizing effect on postural sway (Raper and Soames 1991). Moving sound sources can lead to illusions of self-motion, especially with limited spatial feedback from vision, but feedback from sensory modalities other than hearing about the reference frame ruin this illusion (Väljamäe 2009; Lackner 1977). Directionality of a moving sound source alone does not seem to matter in reducing sway; clockwise and counterclockwise moving auditory stimuli reduce postural sway variability (Tanaka et al. 2001). However, sound that moves from the front toward the back of participants can result in participants leaning toward the approaching sound (Agaeva et al. 2006), which helps explain why Soames and Raper reported a destabilizing effect of a sound stimulus that jumped between speakers anterior and posterior to participants (Soames and Raper 1992). In the current study, we used headphones to eliminate the possibility of the noise stimulus indicating a single fixed or moving location.

Another explanation is that increased attentional arousal during the noise condition could explain the improved stability. McNevin and Wulf (2002) show that an external focus of attention (on the results of an effector on an object) when compared to an internal focus of attention (on the movement of the effector) can lead to reliance on more automatic control processes, which results in improved stability. Others have found that adding a cognitively demanding task leads to more automaticity in balance processes (Cluff et al. 2010). Because passively listening to auditory noise does not involve performance-related (external or internal) attention and is not cognitively demanding, we would not predict that attention in the noise condition would drive a stabilizing effect. However, we cannot summarily rule out the possibility of attentional arousal being involved in some way. Further experimentation is required to shed more light on this.

Stochastic resonance is an explanation for the noise effect on postural sway that fits appropriately and describes the results of much of the literature. SR describes the amplification of signals with the addition of noise. Noise is often viewed in signal processing as something that obscures a signal, but evidence shows that in some systems, noise can contribute to signal optimization. The concept of SR originated in the field of physics (Benzi et al. 1981), where it was used to explain weather patterns in which an accumulation of noise, in the form of heat, leads to certain types of climate shifts. The mechanism has been explained in general theoretical terms as a result of (1) background noise, (2) a weak signal, and (3) a threshold system in which a barrier must be reached for signal transfer (Hänggi 2002). The mechanism was then studied in biological systems because of the prevalence of noise, weak signals, and action potential firing thresholds. It has been demonstrated in nonhuman (Douglass et al. 1993; Levin and Miller 1996; Russell et al. 1999; Bezrukov and Vodyanoy 1995; Schmid et al. 2001; Jung and Shuai 2001) and human (Hidaka et al. 2000; Collins et al. 1996; Richardson et al. 1998; Simonotto et al. 1997) nervous systems. These studies show that sensory perception in a number of species utilizes noise to optimize performance. SR has been studied in vision, audition, and mechanical sensory perception and could be an integral part of sensory perception across species.

Stochastic resonance has been explored for clinical purposes to enhance sound detection in cochlear implant users (Morse and Evans 1996) and in improving postural stability for people with balance problems. Subsensory mechanical noise chips on the bottom of the feet reduce sway in clinical and typical populations (Priplata et al. 2002, 2003, 2006). The explanation for this could be that noise increases somatosensory feedback from the feet. More specifically, the mechanical noise could be contributing to reaching action potential firing thresholds needed for somatosensory feedback, resulting in increased feedback and increased postural control. Similarly, auditory noise can improve postural stability in patients with cochlear implants (Mangiore 2012), which could be the result of increased auditory feedback.

Our data show that visual and auditory feedback interactively contributes to overall sway variability. However, upon examining sway separately in low (<0.3 Hz)- and high (>0.3 Hz)-frequency bands, it was demonstrated that vision and auditory noise reduce radial sway variability in low frequencies interactively and in high frequencies independently. Therefore, the effect of noise is utilized with vision for feedback-based processes, but is additive for open-loop or exploratory processes in postural sway. Further investigation is needed to determine whether the noise effect and its differential influence on the two balance control timescales holds if the auditory signal is subthreshold or masked by other sounds. This work would contribute to a deeper understanding of the mechanisms involved but would also have implications for practical implementation in clinical practice.

Although SR explains our results, as well as the results others have found, it will take a series of targeted studies to determine whether noise is the critical component driving improved stability, whether this is due to SR mechanisms, and specifically how SR works in the auditory modality. We present SR as a possible explanation and do not intend to overextend our interpretation. However, whether or not the effects are due to SR, the current findings have profound implications for improving balance in clinical populations. Auditory noise has the potential for fall prevention for people with instability due to visual, vestibular, or somatosensory deficits. Peripheral sensory deficits can lead to more reliance on audition for balance (Dozza et al. 2007; Hegeman et al. 2005; Palm et al. 2009), and auditory noise can reduce postural fluctuations, so auditory noise should be tested for its ability to improve balance in these populations.

If it is the case that SR is the reason auditory noise reduces sway, then auditory noise also has the potential for fall prevention for people with instability due to central causes. The support for this is that mechanical noise can reduce sway both in people with peripheral and central deficits (Priplata et al. 2003, 2006), and SR is a mechanism that works both in somatosensory (Douglass et al. 1993; Levin and Miller 1996) and auditory system signal transfer (Mangiore 2012). It should be explored whether auditory noise can reduce sway variability in people with instability due to central nervous system damage. Future research should investigate the influence of auditory noise on postural sway in people with centrally caused balance disorders. Finding reduced postural sway in this population would provide further support for SR as an explanation and could easily be extended to clinical applications.

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