Neuroscience Letters 630 (2016) 216–221

Contents lists available at ScienceDirect

Neuroscience Letters

journal homepage: www.elsevier.com/locate/neulet

Research article

Auditory white noise reduces age-related fluctuations in balance

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HIGHLIGHTS

- Auditory white noise reduces postural sway variability in young adults and adults over 65, even in the absence of vision.
- Auditory white noise reduces both feedback-based and exploratory sway variability.
- Older adults' sway patterns more closely reflect those of young adults in the presence of auditory white noise.

ARTICLE INFO

Article history:
Received 1 June 2016
Received in revised form 21 July 2016
Accepted 29 July 2016
Available online 2 August 2016

Keywords:
Balance control
Postural sway
Aging
Falls
Stochastic resonance
Auditory white noise

ABSTRACT

Fall prevention technologies have the potential to improve the lives of older adults. Because of the multisensory nature of human balance control, sensory therapies, including some involving tactile and auditory noise, are being explored that might reduce increased balance variability due to typical age-related sensory declines. Auditory white noise has previously been shown to reduce postural sway variability in healthy young adults. In the present experiment, we examined this treatment in young adults and typically aging older adults. We measured postural sway of healthy young adults and adults over the age of 65 years during silence and auditory white noise, with and without vision. Our results show reduced postural sway variability in young and older adults with auditory noise, even in the absence of vision. We show that vision and noise can reduce sway variability for both feedback-based and exploratory balance processes. In addition, we show changes with auditory noise in nonlinear patterns of sway in older adults that reflect what is more typical of young adults, and these changes did not interfere with the typical random walk behavior of sway. Our results suggest that auditory noise might be valuable for therapeutic and rehabilitative purposes in older adults with typical age-related balance variability.

1. Introduction

With aging comes an increased risk of falling. Falls lead to declines in health and reduced independence and mobility, especially in adults over 65 years of age [1,2]. It has long been posited that postural variability is greater in older adults, although the reasons for that are varied [3]. In recent years, researchers have looked into ways of reducing this variability using a variety of means [4–9]. Balance control relies on continuous streams of multisensory information from visual, vestibular, somatosensory and auditory modalities [8–10], and is sensitive to changes in feedback in any of these modalities [3,8–14]. It has been observed that tactile and auditory noise can both lead to reductions in sway variability [4–7].

A seminal study looked at the potential of stochastic resonance for incorporation into fall prevention technologies [4–7]. Stochastic resonance is when uncorrelated noise boosts transmission of weak signals in threshold-based systems [15,16], and is known to play a role in enhancing weak signals in the peripheral nervous system [17–21]. Priplata and colleagues used vibrating insoles to reduce sway variability in healthy elderly adults and adults with sensorimotor deficits due to peripheral and central causes [4–6]. The mechanical noise produced by these insoles is at 90% of sensory threshold, but these insoles are designed to use stochastic resonance to increase sensory feedback from the feet. The increased feedback from the feet gets incorporated into complex balance control processes, leading to less variability in standing balance.

In a manner similar to somatosensory noise, auditory noise has also been shown to reduce sway variability in cochlear implant users [22] and healthy young adults [7], possibly due to a mechanism similar to stochastic resonance. Auditory noise has not been used previously to reduce sway variability in older adults, but has the potential to compensate for reduced sensory feedback due to

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http://dx.doi.org/10.1016/j.neulet.2016.07.060

visual, vestibular, somatosensory or auditory deficits [8,9,23,24] that lead to postural instability in this age group [25].

In the current experiment, we examined sway variability during silence and while listening to auditory noise, with and without vision, in young adults and adults over 65. We hypothesized that auditory noise would lead to reduced sway variability, even in the absence of vision in both age groups. In addition, we expected the reduction to be greater in adults over 65 because of more variable sway [25] in all four conditions.

2. Methods

2.1. Participants

Fifteen healthy young adults (mean age 19.87 ± 2.10 years) and fifteen adults over the age of 65 (mean age 78.67 ± 7.73) of similar height (t(28) = 2.92, p = 1.44) and weight (t(28) = 2.43, p = 0.13) were recruited from the University of California, Merced student population and the Merced local population, respectively. The older adult participants had a range of typical age-related impairments including mild hearing loss (that did not interfere with conversational speech), mild vision impairment (with corrective lenses), arthritis, orthopedic conditions, nerve pain and history of heart attack. Young adult participants had no hearing impairments, arthritis, orthopedic conditions, or neurological disorder. No subjects reported recent injuries or skeletomuscular disorders and all could stand unassisted during the experiment. The experimental protocol was carried out in accordance with the Declaration of Helsinki, reviewed by the UC Merced IRB, and all participants gave informed consent prior to testing.

All participants were screened for vision impairment using the Rosenbaum Pocket Vision Screener, and were asked to complete a standing balance test (balancing on one leg at a time, three times per leg) to screen for major balance problems that would put participants at increased risk for injury during the experimental protocol. Experimenters and all participants were comfortable participating and did not feel unsafe completing the protocol. However, there were group differences in ability to stand on one leg at a time, which we believe is representative of real-world differences between young and older adults. Young adults and older adults differed in the average amount of time they could balance on the left leg (t(28) = 9.84, p = 0.004) and on the right leg (t(28) = 8.62, p = 0.007). The older adult participants completed the Falls Efficacy Scale- International (FES-I), a standard questionnaire designed to quantify daily fear of falling in older adults [26,27]. Scores averaged 25.28 ± 9.18, indicating a range of fear spanning low concern, moderate concern, and high concern. The protocol was approved by the Institutional Review Board.

2.2. 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 designed to reduce noise from external sources. 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. Conditions were presented in a randomized order. Trials lasted 30 s and were either accompanied by auditory white noise (10 trials) or silence (10 trials). Postural sway data were collected in a single session with 20 30-s 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, presented at 75 dB through the headphones. Participants were exposed to the noise stimulus prior to the experiment to verify that the noise stimulus was not uncomfortable for them.

2.3. Analyses

Center of pressure (CoP) was sampled at 2000 Hz with an AMTI Force and Motion platform (Optima BP400600-2000). The first 4 s of each trial were removed to eliminate any potential startle response the participants might have had to the stimulus onset. Raw data was down sampled to FS = 50 Hz and normalized. Standard deviation from mean CoP of anterior-posterior (A-P) and medial-lateral (M-L) sway was calculated for each time step, and radial sway (r) of the CoP was calculated for each time step (i) using A-P (x) and M-L (y) components of sway following

$$r_i = \sqrt{x_i^2 + y_i^2}$$

Average A-P, M-L, and radial sway were calculated for each trial and were used to assess variability in postural sway during the trials [28]. Trial outliers outside ±2 standard deviations from each subject's mean were removed.

Radial sway in low- and high-frequency ranges was examined separately to assess changes in slower and faster timescales of postural control [11,25,29]. 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. [29]. We used low- and high-pass Butterworth filtering routines, as in Yeh et al. [11,25], to decompose sway into low (<0.3 Hz)- and high (>0.3 Hz)-frequency sway. Detrended fluctuation analysis (DFA) was used to quantify the sway patterns over time. The data were down sampled for this analysis to 25 Hz.

3. Results

3.1. Analysis of postural variability

A-P, M-L, and radial sway variability were reduced with the addition of auditory noise (Fig. 1). Standard deviation in the A-P and M-L sway and radial sway was compared across condition and between groups using two-way analyses of variance (eyes closed vs. open and silence vs. noise) with repeated measures, with age group as the between subjects factor. We found main effects of vision ($F(1,28) = 9.36$, $p = 0.005$) and noise ($F(1,28) = 5.93$, $p = 0.022$) on A-P sway, a main effect of noise ($F(1,28) = 8.86$, $p = 0.006$) on M-L sway, and main effects of vision ($F(1,28) = 10.47$, $p = 0.003$) and noise ($F(1,28) = 9.01$, $p = 0.006$) on radial sway. We did not find any vision × noise interactions. We found greater A-P sway ($F(1,28) = 21.27$, $p < 0.001$) and radial sway ($F(1,28) = 9.03$, $p = 0.006$) in the older adults than in the young adults. See Fig. 2 for radial sway of young and older adults.

When variability in low (<0.3 Hz) and high-frequency (>0.3 Hz) sway was analyzed separately, we found reductions in sway variability in both frequency bands, indicating that vision and noise can influence both feedback based and exploratory balance processes. We found a main effect of vision on low frequency A-P sway ($F(1,28) = 5.91$, $p = 0.022$) and on high frequency A-P sway ($F(1,28) = 20.11$, $p < 0.001$), a marginal effect of noise on low frequency A-P sway ($F(1,28) = 2.19$, $p = 0.073$), and a strong effect of noise on high frequency A-P sway ($F(1,28) = 11.03$, $p = 0.003$). There was a vision × noise interaction in high frequency A-P sway, a between subjects effect in low frequency A-P sway ($F(1,28) = 13.69$, $p = 0.001$) and marginally in high frequency A-P sway ($F(1,28) = 3.72$, $p = 0.064$), with more A-P sway in older adults than young adults.

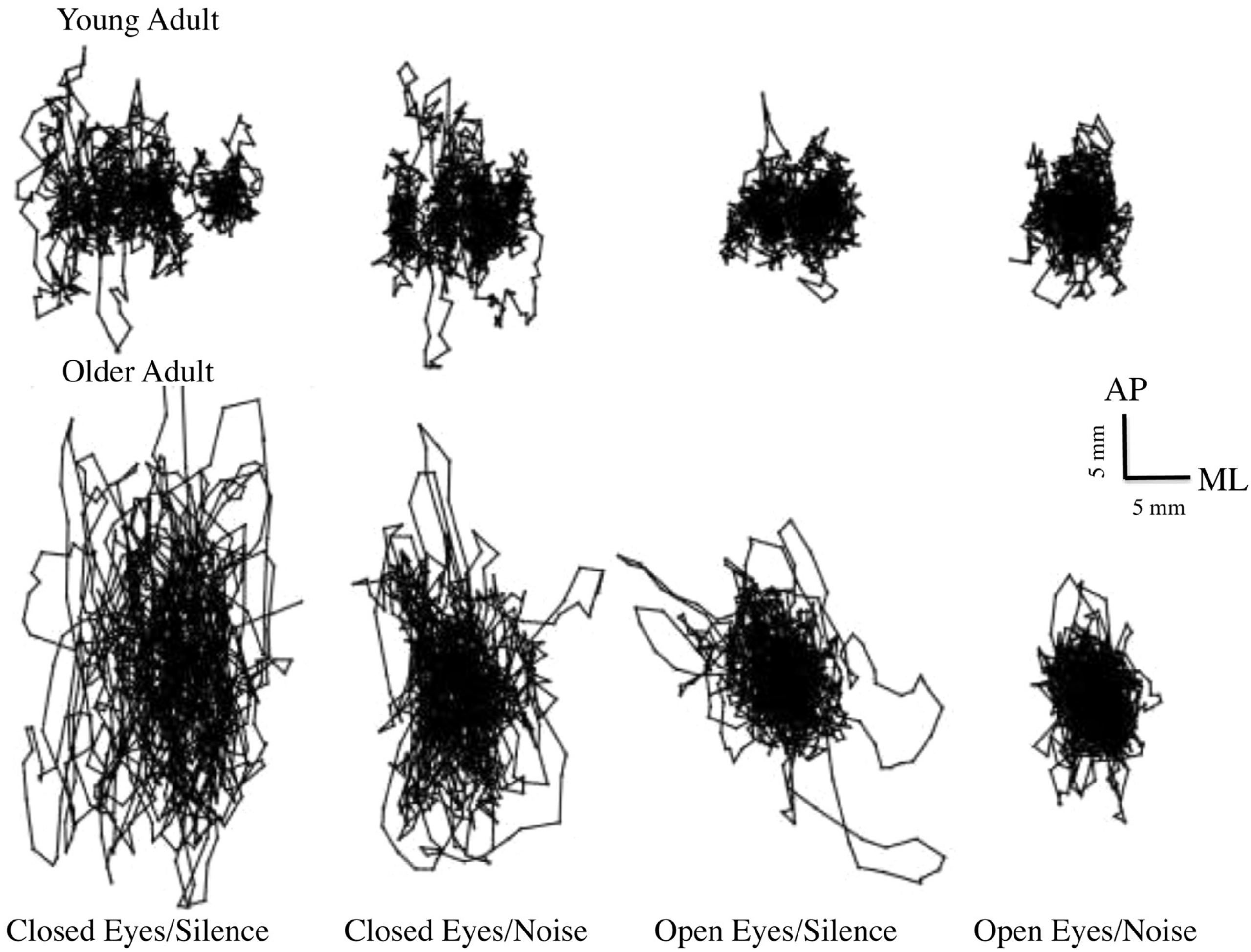

Fig. 1. Center of pressure displacement exhibited by representative young and older adult subjects with eyes closed and open and in silent and noise conditions.

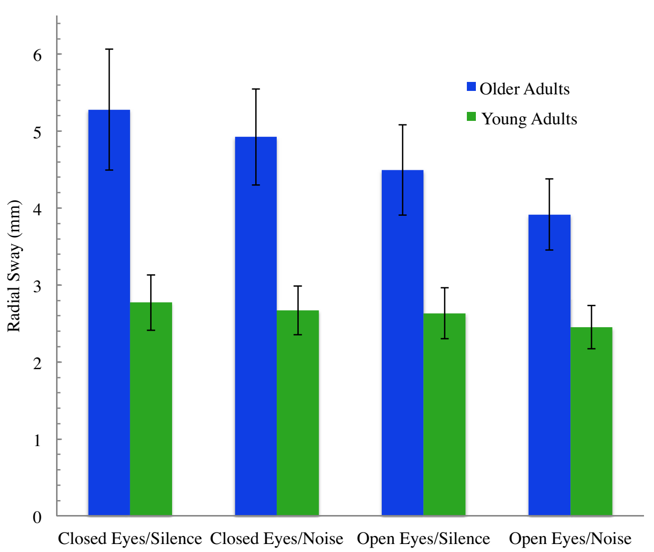

Fig. 2. Radial sway variability in eyes closed/eyes open and silent/noise conditions for young and older adults. Error bars represent ±1 standard error from the mean.

We found a main effect of noise on low frequency (F(1,28) = 8.41, p = 0.007) and high frequency (F(1,28) = 4.31, p = 0.047) M-L sway, and a between subjects effect in low frequency M-L sway (F(1,28) = 6.77, p = 0.015), with no vision × noise interactions.

In radial sway, there were main effects of vision on both low (F(1,28) = 4.37, p = 0.046) and high (F(1,28) = 14.58, p = 0.001) frequency radial sway, and main effects of noise on both low (F(1,28) = 7.91, p = 0.009) and high (F(1,28) = 8.01, p = 0.008) frequency radial sway. There were no vision × noise interactions, and there was a between subjects effect in low (F(1,28) = 13.21, p = 0.001) frequency radial sway, with a marginal between subjects effect in high (F(1,28) = 3.71, p = 0.064) frequency radial sway. See Fig. 3 for radial sway of young and older adults in low and high frequencies.

3.2. Detrended fluctuation analysis

Detrended fluctuation analysis showed that all sway measures (A-P, M-L, and radial) exhibit anti-persistent fractional Brownian motion (fBm, $1 < \beta < 1.5$). This semi-random walk pattern is characteristic of postural sway [30–32]. Within this 1–1.5 range, there were differences between conditions and subjects in β. The value of β was compared across conditions and age group using a two-way ANOVA (eyes closed vs. open and silence vs. noise) with repeated measures, with age group as the between subjects factor. We found higher β in older adults than in younger adults for A-P sway (F(1,28) = 11.21, p = 0.002) and radial sway (F(1,28) = 7.63, p = 0.010). We found a main effect of noise on radial sway β (F(1,28) = 4.71, p = 0.039), and marginal effects of noise on A-P β (F(1,28) = 3.65, p = 0.066) and M-L β (F(1,28) = 2.98, p = 0.095), and a vision × noise interaction for A-P β (F(1,28) = 12.15, p = 0.002). Vision and noise reduce β so sway is more similar to that of healthy

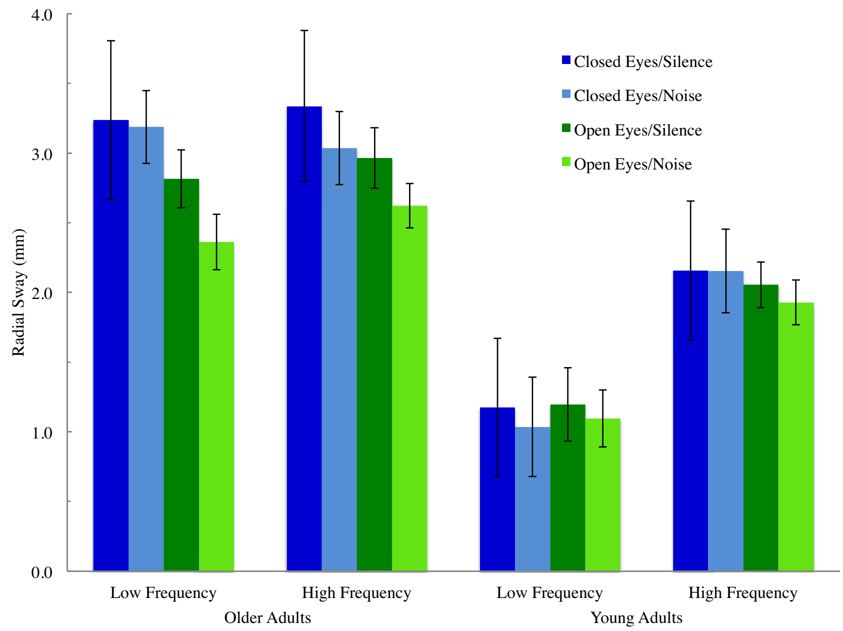

Fig. 3. Radial sway variability in low (<0.3 Hz) and high (>0.3 Hz) frequency ranges in eyes closed/eyes open and silent/noise conditions for young and older adults. Error bars represent ±1 standard error from the mean.

young adults, while not interfering with the typical random walk pattern of postural sway.

4. Discussion

We clearly demonstrate reduced postural sway variability in young and older adults over 65 with auditory noise. This reduction in variability was present with and without vision. Standing balance has been described using an inverted pendulum model, where sway movements are dictated by the dynamics of the joints and muscles of the lower limbs [33,34]. However, a large body of literature on postural sway shows that sensory information is incorporated into balance maintenance in real time [3,8–14,35], and that sensory feedback delays effect low and high frequency components of sway differentially in both young [11,29] and older adults [25], supporting that there are two timescales of sway that reflect different balance processes [29,33]. Slower timescales of sway are thought to reflect drift of the inertial mass of the body, at the center of mass [34], and are more susceptible to changes in sensory feedback [11,25,29]. Faster timescales of sway are thought to reflect smaller adjustments around the center of mass that are more directly related to joint rigidity and muscle tone [36,37]. Some researchers have argued that the faster timescale movements could be representative of anticipatory or exploratory processes [29]. Using low- and high-pass Butterworth filters with a cut-off frequency of 0.3 Hz, these two timescales of sway can be examined separately [11,25,29]. Our results show that auditory noise and vision can influence both slower and faster timescale components of sway. We also show changes with auditory noise in nonlinear patterns over time in older adults to reflect what is more characteristic of young adults while maintaining the typical random walk pattern. These results support that auditory noise could be a valuable aid for adults over 65 who suffer from instability by improving balance without disrupting healthy balance processes.

Balance control relies on both exogenous and endogenous fluctuations–fluctuations with sources external to the body and fluctuations that are inherent in the control of balance [38]. Sources that have been shown to influence postural control that are exogenous include changes in visual, auditory and tactile feedback [8–14,23,24,40–42]. Sources that could be considered endogenous include cognitive load [11,39,43] and attention [44]. The temporally correlated nature of postural sway patterns is a reflection of endogenous influences on balance control. Because stochastic resonance also relies on both endogenous and exogenous fluctuations, the strength of the effect is influenced by a range of individual differences and environmental factors. In addition, the strength of the effect is also influenced by interactions between exogenous signals and the temporal correlations of endogenous fluctuations [38]. It would be very interesting to see the effect of cognitive load on postural fluctuations in the presence of auditory noise.

In a re-analysis of Priplata et al. [5] by Kelty-Stephen & Dixon [38], older adults' postural sway patterns show an increase in temporal correlations when compared with younger adults, and temporal correlations in sway patterns moderate the stochastic resonance effect of the vibrating insoles. Our data show a proportionally greater reduction in sway variability when noise was presented to older adults than young adults.

It is important to underscore that variability and stability in standing balance do not necessarily have an inverse relationship, as variability in sway patterns may be needed for adaptability and increased control in the presence of perturbations [45,46]. However, increased variability in standing balance has been linked with increased likelihood of falls [47–51]. Our results support that a reduction in variability with auditory noise is accompanied by changes in nonlinear patterning that is more typical of healthy young adults. Auditory noise reduces variability in young and older adults and leads to sway patterns more typical of younger adults while still maintaining a random walk pattern.

Stability can be understood as the coadjustment of local variability and serial correlation properties [52]. Amoud et al. [53] found a similar pattern of group differences when analyzing COP in young and older adults. In this study, DFA of sway from young and older adults revealed higher H in the older adults' sway than in the younger adults' sway. Higher H indicates more persistence, or more correlation between successive points, and a lower H indicates more anti-persistence in a signal. Anti-persistence can be interpreted as more tightly controlled, or less resistant to changes in COP displacement direction, which reflects adaptability of the signal to change. Due to the direct relationship between H and β, a lower β can be interpreted in the same way as a lower H. Our DFA results contribute to the question of variability and adaptability by suggesting that the reduction in sway variability with noise in the older adults is accompanied by increased adaptability. Importantly, however, we emphasize that β was between 1 and 1.5 in all conditions; all sway was anti-persistent and the differences between groups show only differences between degree of anti-persistence within this range. Auditory white noise did not interfere with the random walk property of sway, but might have influenced adaptability as well as variability leading to increased postural stability.

It should be explored whether auditory white noise can be used to reduce variability and adaptability in older adults with centrally caused balance disorders, such as due to stroke or Parkinson's disease. Finding similar variability reduction in these groups would provide evidence for the generalizability of the noise effect on balance variability of different causes. It would also lend further support for stochastic resonance as a valid mechanistic explanation. Finally, practical application of auditory white noise for balance should be explored for therapeutic and rehabilitation purposes for adults who suffer from balance instability.

Authors' contributions

All authors read and approved the final manuscript. J.R., R.B., design of experiment; J.R., O.W., Z.M., collection of data; JR, RB, analyses; RB, project supervision; J.R., O.W., Z.M., R.B., joint contribution to writing the manuscript. The authors have no conflict of interest to declare.

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