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Original Article

Influence of Auditory Information on Postural Control During Different Gait Tasks in the Elderly

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BACKGROUND: Hearing loss is frequently associated with reduced postural control. This is possibly not only related to simultaneous pathophysiological changes within the hearing and vestibular system. The auditory input itself could provide helpful information for maintaining postural control. Previous studies of our group already showed that continuous or interrupted white noise can significantly improve postural control during gait conditions in young healthy individuals. The present study aimed at investigating if those effects are also active in the elderly.

METHODS: Elderly volunteers (mean age 67 years) without any history of disorders to influence gait performance successfully completed 5 walking tasks under 4 different acoustic conditions. Angular sway velocity was measured close to the center of gravity with the Vertiguard® system.

RESULTS: Significant changes in body sway velocity were found in 4 of 5 investigated tasks. Only "walking with turning head in rhythm" was not associated with any change in the acoustic input. The sway increased by 8.9% during "walking with open eyes" in the pitch direction and by 11.5% during "tandem walking" in the roll direction if ear protection was applied. The sway was reduced by 9.1% during "walking over barriers" in the pitch direction and by 16.7% in the roll direction during "walking with closed eyes" if a stationary source of continuous white noise was presented.

CONCLUSION: The data of the present study indicate that auditory information could significantly alter postural control during walking in the elderly. Continuous white noise seems to be helpful for maintaining balance in different walking tasks.

KEYWORDS: Auditory influence, postural control, age effects, walking

INTRODUCTION

Hearing loss (HL) is frequently associated with reduced balance performance[1,2] with or without perceived dizziness.[3] A systematic review found a significant positive association between HL and postural control in older adults.[1] Hearing loss is a risk factor for falls, particularly in the elderly.[4,5] Moreover, HL is an independent risk of frailty in older adults and with greater odds of falling over time.[6] Lin and Ferrucci[7] reported that people with HL have an increased risk-to-fall in the order of 1.4× per 10 dB HL (above a 25 dB HL threshold). The 10 years-risk to fall attributable to HL is 6.9/100 (i.e., a 70%-80% increase compared to normal age-related hearing).[8] An amplification of hearing by hearing aids or implants can possibly improve balance.[9] Decreasing the risk of fall in the elderly with HL requires a better understanding of the mechanisms underlying the association between hearing and balance. It was proposed that the association between HL and balance problems is possibly mediated by an underlying vestibular dysfunction with or without vestibular symptoms. Especially a high-frequency HL was significantly correlated with saccular, but not utricular or semicircular canal dysfunction.[10] A strong correlation over the whole lifespan was also described between the decline of vestibular and spiral ganglion cells as well as inner and outer hair cells.[11] However, a correlation between the number of vestibular ganglion cells and hearing thresholds was only found in normally hearing individuals with bone conduction thresholds of 25 dB or less (250 – 8000 Hz). Thus, poor hearing was not associated with a decrease in vestibular ganglion cells.[11] This indicates that the relationship between hearing levels and postural control does not only depend on simultaneous pathophysiological changes. Specific auditory cues could participate in the process of sensory integration for postural control, particularly in the elderly or adults with impaired sensory input. A previous study already showed a clear contribution of some well-defined acoustic signals to postural control during specific gait conditions in young healthy individuals.[12] The body sway decreased significantly during walking with open eyes, tandem steps, and walking over barriers when continuous or interrupted white noise (60 dB SPL) was presented from a fixed sound source at the end of the walking distance.

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The present study aimed at investigating if those effects are also active in the elderly. The results could contribute to the identification of specific auditory cues which are helpful for maintaining balance in this aging population and, thus, self-motion perception.[13]

METHODS

Subjects

In this study, 16 subjects (12 females and 4 males, mean age = 67.1 years, range = 62-79 years) with normal or corrected visual acuity of at least 0.7 logMAR (tested with Landolt rings) and no vestibular complaints were recruited. No or mild dizziness handicap levels were found by means of the Dizziness Handicap Inventory (DHI).[14] The mean DHI sum score was 6.5 ± 7.5 standard deviation (SD). All subjects had no history of vertigo at any time.

Exclusion criteria were acute medical diseases (e.g., infections) or specific chronic diseases (e.g., depression, ataxia, stroke) that might influence the audio-vestibular system and/or the ability to walk. Furthermore, any medically prescribed drug intake influencing the balance system was an exclusion criterion as well.

Fifteen subjects were excluded from the study based on the above-mentioned criteria. Six subjects reported a history of stroke, an ongoing depression, or ataxia (2 in each criterion). Nine subjects had poor corrected visual acuity (higher than 0.7 logMAR).

The saccular and utricular function was tested by recording cervical (cVEMPs) or ocular vestibular evoked myogenic potentials (oVEMPs) with an ECLIPSE® measurement system (Interacoustics, Middelfart, Denmark). Five subjects had absent oVEMPs and 6 subjects had absent cVEMPs unilaterally. The anterior, posterior, and horizontal semicircular canals, respectively, were analyzed by the video head impulse test system ICS Impulse® (Otometrics, Planegg, Germany). No pathologic results were found.

Performance during posturographic measurements in stance and gait tasks by the geriatric Standard Balance Deficit Test (gSBDT)[15] with the Vertiguard® system (Zeisberg GmbH; Metzingen, Germany) showed for all participants a normal composite score (below 50). The following formula was applied by the device to calculate the composite score for the estimation of the total performance of a patient in relation to normal controls:

$$SBDT\ composite\ score = \frac{\left(\sum_i pi + \sum_i ri\right)*100}{n*400}$$

with p = pitch sway/normal value in %, r = roll sway/normal value in %, n = number of tasks.

MAIN POINTS

- Auditory information influences postural control during walking in the elderly.
- Reduction of the auditory input increases body sway.
- Stationary white noise improves postural control.

Subjects with a composite score below 50 have an impaired balance during the gSBDT of the Vertiguard® system. This is based on the result of the formula above for 100% age and gender-related sway. The average score of all included subjects was 47.4 ± 4.1 SD.

The Institutional Review Board approved the study protocol (approval number EA4/182/17). All experiments were carried out in accordance with the Declaration of Helsinki and all participants agreed to the informed consent.

Procedure and Setup

Pure tone air- and bone-conducted audiometric thresholds at 0.25, 0.5, 1, 1.5, 2, 3, 4, 6, and 8 kHz were determined via headphones in an audiometric booth. All participants showed a normal age-related HL without a relevant air-bone gap. The asymmetry of hearing thresholds between both ears was below 10 dB. To characterize the hearing ability of the study sample, air-conducted hearing thresholds of the 4 common frequencies are shown in Table 1.

The experimental protocol included 5 walking tasks under 4 different acoustic conditions.

Participants performed the following test battery:

- walking with eyes open/closed over a distance of 12 m,
- walking with eyes open with turning head to the right and to the left in rhythm over a distance of 12 m,
- walking with eyes open over barriers over a distance of 12 m, and
- tandem steps (toe to heel) with eyes open over a distance of 6 m

During the test procedure, the participants wore similar disposable socks and pants to diminish the influence of different individual

Table 1. Air Conduction Pure Tone Hearing Thresholds in the 4 Common Frequencies on Both Tested Sides (Right (R), left (L)) of All Included Patients

No.	0.5 R	0.5 L	1 R	1 L	2 R	2 L	4 R	4 L	Mean R	Mean L
1	10	5	10	10	25	20	40	40	21.3	18.8
2	15	15	15	20	25	35	15	25	17.5	23.8
3	15	5	10	10	5	10	35	35	16.3	15.0
4	0	5	5	5	10	10	30	20	11.3	10.0
5	10	10	15	10	30	20	50	45	26.3	21.3
6	15	10	30	15	40	30	45	25	32.5	20.0
7	15	10	15	10	15	10	30	30	18.8	15.0
8	15	15	15	15	25	15	45	50	25.0	23.8
9	15	15	20	15	5	15	10	15	12.5	15.0
10	10	10	10	5	10	15	15	15	11.3	11.3
11	0	5	5	10	10	10	35	30	12.5	13.8
12	10	5	15	10	45	20	40	35	27.5	17.5
13	10	5	10	5	5	5	15	20	10.0	8.8
14	20	15	15	15	20	25	25	50	20.0	26.3
15	5	5	5	5	10	5	20	15	10.0	7.5
16	40	40	40	40	30	30	35	35	36.3	36.3

shoes and clothes on sway measures. All tasks were recorded under following acoustic conditions:

- in quiet as reference condition (R),
- with a loudspeaker in front presenting continuous white noise (cN),
- or interrupted white noise (iN),
- gained walking noise by presenting a click at each step (gN),
- and participants wore earplugs (Howard Leight Max) and additionally circumaural ear protectors (EP) (Moldex M1).

Each acoustic condition was preceded by a separate reference condition.

The loudspeaker (JBL Control One) was placed 2 m behind the end line. Continuous and interrupted noise consisted of white broadband noise with a frequency range of 80 Hz to 20 kHz. For the interrupted noise condition, noise and pause alternated every 0.5 s. The noise was presented at 60 dB SPL. The acoustic insulation value of earplugs combined with circumaural EPs for white broadband noise amounted to 45 dB over all frequencies. In order to avoid a different performance by different light irradiation through the windows in the test room, all windows were darkened and artificial light of a similar amount was applied by 4 evenly distributed ceiling lights to illuminate the room.

Sway values of the first 2 steps and the last step of all walking tasks were not included in the analysis to avoid starting and stopping artifacts. The acoustic conditions changed at the midpoint of the walking path between silence as reference condition (R) and one of the other conditions.

During the performances, the time course in each analyzed section was recorded to ensure a similar walking speed. Participants were instructed to walk at their individual normal pace. Time differences of up to 10% between the first and the second section were accepted.

The sway during walking is highly indicative of postural control, especially in the elderly where a higher walking sway increases the risk to fall during disturbances. Since walking speed is also a predictive factor for falls, this variable was kept constant as possible.

Body sway was recorded with the VertiGuard® system. This device measures the momentary angular velocity ω [°/s] in the anterior-posterior (ap, pitch) and the lateral (roll) direction close to the body's center of gravity with a sampling rate of 80 Hz. Participants wore the device with a belt on the hip (Figure 1). The intended use of the device is the assessment of postural control during different stance and gait conditions for diagnostic purposes. Individual balance deficits are detected in any of the specific daily-life-related tasks by comparing the sway results with inbuilt sex- and age-related normative values.

For further calculations, the absolute values of angular velocities were averaged for each plane. The use of absolute values avoids the occurrence of negative values since 1 direction of the same plane (e.g., left direction) has a negative angular velocity while the other (e.g., right direction) has a positive angular velocity. Percentage changes were calculated in relation to the preceding reference condition. This was performed to enable easier comparison between the effects on different sensorimotor conditions.


[redacted]

Figure 1. Picture of the Vertiguard®-device and the wearing position during testing. The numbers on the device are for selecting training tasks during vibrotactile feedback training. This function was not relevant and thus not enabled during the present study.

All tasks and acoustic conditions were performed in a randomized order. During the measurements, a video- and a sound-level recording system were used to search afterward for incorrectly performed tasks or recordings with unintended background noise. No incorrectly performed tasks or background noise was detected in the recordings.

Room Properties

All tasks were performed in a hallway, which was approximately 2.5 m wide and 16.5 m long. This room had a reverberation time of T30 (125-8000 Hz) = 2.46-1.05 s. In silence, the sound level was below 35 dB SPL and was monitored by a calibrated sound level recording system.

Statistical Analysis

Data analysis was performed with MATLAB R2014b and IBM Statistical Package for the Social Sciences version 23 (IBM SPSS Corp.; Armonk, NY, USA). Data distribution was tested with the Kolmogorov–Smirnov test. The *t*-test for dependent samples or the Wilcoxon test was used (depending on data distribution) for the comparison between the sway during an acoustic condition and the corresponding reference condition. For each comparison (R/cN, R/iN, R/gN, and R/EP), data were recorded in separate trials as described earlier. Hence, the measured values of the reference condition were not compared more than once with another condition. Therefore, a correction for multiple comparisons was not necessary.[16]

Audiometric pure tone thresholds were averaged individually over all tested frequencies and both ears. A regression between body sway *change* and this bilateral mean air-conducted hearing thresholds was performed in all tasks and conditions which showed a significant influence of the acoustic condition on body sway. To calculate the body sway *change*, all sway values of the experimental condition were subtracted from those of the reference condition. This analysis aimed to find a possible relationship between the subject´s hearing ability and the effect of an acoustic condition on body sway. This could be particularly helpful for validating the results (e.g., subjects with poor hearing ability should not be highly influenced by wearing EPs). Pearson's correlation coefficient was calculated if the determination coefficient indicated a linear relationship between the values ($R^2 > 0.2$). The significance level for all statistical calculations was $P < .05$.

RESULTS

Significant changes in body sway velocity were found in 4 of 5 investigated tasks. Only "walking with turning head in rhythm" was not affected by any change in the acoustic input. Ear protection increased the sway by 8.9% (effect size 0.66) during "walking with open eyes" in the ap direction and by 11.5% (effect size 0.61) during "tandem walking" in the medio-lateral direction (Tables 2 and 3). The presence of a stationary source of continuous white noise reduced the sway by 9.1% (effect size 0.46) during "walking over barriers" in the ap direction and by 16.7% (effect size 1.24) in the lateral direction during "walking with closed eyes" (Tables 2 and 3). For the evaluation of these percentage changes, the difference between the mean sway during "walking with closed eyes" and "walking with open eyes" in the quiet reference condition was calculated. The absolute difference between these conditions amounted to 10.5% for the ap direction and 14.1% for the lateral condition.

Body sway was not significantly influenced during all tested tasks by the application of interrupted white noise or gained walking noise (Tables 2 and 3).

A linear regression with $R^2 > 0.2$ could not be fitted for continuous noise during "walking over barriers" (ap direction), for "walking with closed eyes" (medio-lateral direction), or "tandem walking" (medio-lateral direction) while wearing EPs (Figure 2A, B and D). The regression coefficient during "walking with open eyes" (ap direction) with ear protection was 0.3. For this condition, a significant correlation could be determined ($r = 0.55$, $P = .041$).

Table 2. Mean Sway Velocity (°/s ± SD) in the Anterior-Posterior Direction During Different Walking Tasks and Acoustic Conditions

	Eyes Open	Eyes Closed	Turning Head	Tandem	Barriers
R	17.3 ± 2.9	15.4 ± 2.6	15.2 ± 2.2	11.0 ± 1.5	40.5 ± 7.4
iN	17.2 ± 3.7	15.5 ± 2.7	16.0 ± 2.9	10.4 ± 1.6	38.6 ± 6.8
% Change	−4.0	0.8	4.9	−5.7	−4.9
R	16.6 ± 2.9	15.5 ± 2.4	16.1 ± 2.6	12.4 ± 2.1	38.5 ± 7.3
cN	17.7 ± 3.6	15.7 ± 2.2	16.7 ± 3.0	12.2 ± 1.4	35.3 ± 6.5
% Change	6.4	1.6	3.9	−1.9	−9.1*
R	17.8 ± 3.4	15.9 ± 2.3	14.7 ± 2.9	12.0 ± 1.7	38.6 ± 6.7
gN	17.3 ± 3.6	15.0 ± 2.5	14.6 ± 3.3	12.1 ± 1.8	38.5 ± 7.5
% Change	−3.2	−6.3	−0.8	0.9	−3.3
R	17.4 ± 2.1	15.6 ± 2.3	20.7 ± 5.7	11.6 ± 2.4	37.7 ± 7.9
EP	19.1 ± 2.9	15.3 ± 2.2	19.6 ± 5.3	12.0 ± 2.4	36.0 ± 7.0
% Change	8.9*	−2.5	−5.5	3.7	−4.5

cN, continuous noise; EP, ear protection; gN, gained walking noise; iN, interrupted noise; R, quiet reference.
Asterisks indicate significant differences ($P < .05$).

Table 3. Mean Sway Velocity (°/s ± SD) in the Lateral Direction During Different Walking Tasks and Acoustic Conditions

	Eyes Open	Eyes Closed	Turning Head	Tandem	Barriers
R	20.3 ± 4.7	18.9 ± 2.9	18.3 ± 3.6	17.6 ± 1.9	32.3 ± 5.8
iN	19.1 ± 4.0	18.2 ± 3.6	19.9 ± 4.1	17.2 ± 2.0	34.1 ± 6.4
% Change	−6.3	−3.8	8.1	−2.1	5.3
R	22.0 ± 3.9	21.1 ± 2.6	23.0 ± 4.4	17.1 ± 2.8	30.5 ± 3.6
cN	21.7 ± 4.2	18.0 ± 2.4	22.1 ± 4.0	17.4 ± 2.0	32.0 ± 6.3
% Change	−1.6	−16.7*	−4.0	2.0	4.5
R	21.3 ± 3.6	16.9 ± 2.3	17.9 ± 4.0	17.3 ± 2.1	31.2 ± 5.6
gN	20.5 ± 3.6	17.2 ± 1.8	18.3 ± 3.7	17.7 ± 3.7	31.6 ± 5.9
% Change	−3.9	1.7	2.4	2.5	1.3
R	23.5 ± 4.5	19.5 ± 2.4	25.8 ± 6.5	16.2 ± 3.3	33.1 ± 5.9
EP	25.1 ± 4.9	19.0 ± 2.4	22.3 ± 3.2	18.3 ± 3.7	33.0 ± 4.5
% Change	6.5	−2.7	−15.7	11.5*	−0.1

cN, continuous noise; EP, ear protection; gN, gained walking noise; iN, interrupted noise; R, quiet reference.
Asterisks indicate significant differences ($P < .05$).

DISCUSSION

The present results showed a specific influence of auditory information on postural control during almost all investigated walking tasks in the elderly. Only "walking with turning head in rhythm" was not significantly affected by any change in the acoustic input. Walking with turning the head is well-known as a difficult dual task in the elderly.[15,17] The information overload prevents the processing of the additional acoustic input.[18] Another reason might be the impaired localization ability during moving the head in rhythm to the right and left in combination with walking.

A source of continuous white noise at the end of the walking range could increase postural stability in simple and complicated walking tasks. The fixed sound source was helpful during "walking with closed eyes" and "walking over barriers." Walking with a reduced visual input is challenging—especially in the elderly—since the vestibular and proprioceptive inputs are reduced. To walk over barriers is an experimental condition for simulating a stair or curb where dangerous falls occur very frequently.[19,20] The increase in stability during these complicated tasks, which make individuals highly prone to falls, is quite important. For both tasks, the absolute effect of the auditory input on body sway was surprisingly in the similar range as the effect of total visual deprivation (open eyes compared to closed eyes) during walking in quiet. Since the effect was that large, one could argue that this is related to the short performance of the task or a surprising change in the acoustic conditions. However, all tasks were performed over the same distance and the conditions were explained before the measurement to the subjects. If the precise occurrence of the signal during performing the task was unknown and surprised the subjects, an increased sway would be expected. The opposite effect was observed. A longer measurement period with self-selected acoustic conditions could possibly validate the effects shown here.

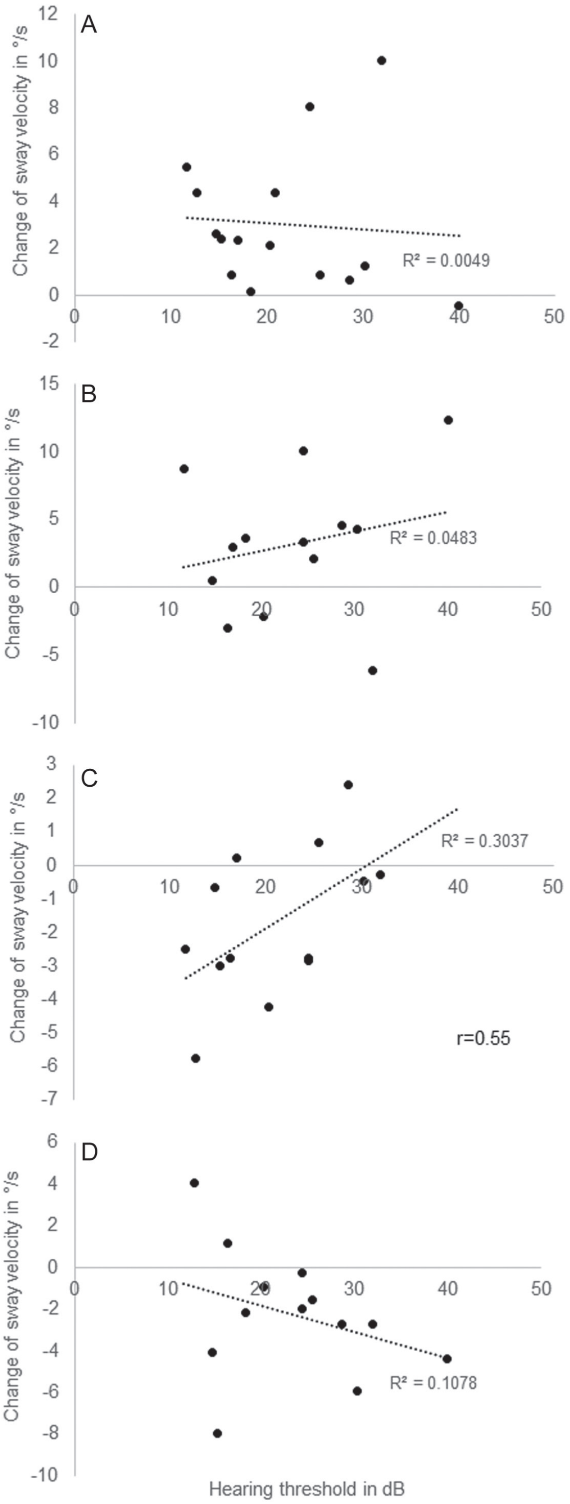

Figure 2. Relationship between body sway change and bilateral mean air-conducted hearing thresholds (0.25-8 kHz) for all tasks and conditions which showed a significant influence of the acoustic condition on body sway ((A) continuous noise during walking with eyes closed (medio-lateral direction), (B) continuous noise during walking over barriers (anterior-posterior direction), (C) walking with eyes open and ear protection (anterior-posterior direction), (D) walking tandem steps with ear protection (medio-lateral direction)). The sway values of the experimental condition were subtracted from those of the reference condition to calculate the sway change. Each point represents 1 participant. A linear regression line was fitted to the data with the stated determination coefficient (R^2). Pearson's correlation coefficient r was calculated if R^2 was >0.2.

A fixed sound source is also helpful for maintaining balance during gait in a younger population.[12] This similar effect is most likely based on the fact that the participants localized the sound source during walking toward the loudspeaker.[21] This was also possible in the elderly population under study with mild to moderate HL since the noise signal was certainly well above the hearing threshold. Thus, the individual hearing threshold was not related to the difference in sway between the noisy and the silent condition. The effect seems to depend only on the signal perception itself. This supports earlier findings which described that the relationship between hearing and postural control is not only related to simultaneous microstructural changes within the hearing and vestibular system.[11,22]

It was hypothesized that interrupted white noise could provide helpful information for postural control since this was previously shown for a younger population.[12] A train of onset signal reflections in an echoic room could provide a helpful change of time differences during body movements. This effect was not shown in the present study. Possibly, interrupted noise, which reduced body sway in the younger population by short reflections, does not generate perceivable reflections for the older participant. Another explanation is that the auditory anchor of a continuous stationary sound source was interrupted and therefore no longer helpful to maintain postural control. However, the effect of interrupted noise was also weak in the younger population. A significant influence could only be detected in young men during "walking over barriers."[12]

Besides the improvement of postural stability by a fixed sound source, the opposite effect was observed if the auditory input was blocked by EPs. The elimination of all residual acoustic information resulted in an increased sway during normal walking (eyes open) and tandem walking. This demonstrated the effect of low intensity, but constant acoustic signals on postural control. The deprivation from the acoustic input induced an absolute change of sway which was nearly in the similar range as the effect of open eyes (compared to closed eyes) during walking in quiet. The positive effect of noise on postural control is possibly related to a changed stochastic resonance within the vestibular system.[23] As expected, the effect of the elimination of low-intensity signals (residual noise in quiet) on body sway depends largely on the individual hearing threshold. The better the hearing, the greater the influence of acoustic deprivation. This holds true for "walking with open eyes" but not for "tandem walking." Tandem walking is a much more difficult task than normal walking. Some participants with better hearing seem to step up their motor abilities upon the elimination of the acoustic input. This effect was paralleled by the finding that the residual acoustic signal was helpful even for participants with poorer hearing in this more challenging task. Further research is required to determine the minimal intensity above the hearing threshold which is necessary for the improvement of postural control by an auditory signal. Another limitation of the present study is the small sample size even if the sample was large enough for the applied statistical testing. Additional studies are required to verify our findings in a larger set of volunteers.

CONCLUSION

In essence, the data of the present study indicate that auditory information could significantly improve postural control during walking in the elderly. Continuous noise at low or moderate intensities seems to be helpful for maintaining balance in easy and challenging walking tasks. Further studies with a larger sample size will elucidate possible clinical implications of the present results.

Ethics Committee Approval: Ethical committee approval was received from the Ethics Committee of the Charite Medical School, University of Berlin (Approval no: EA4/182/17).

Informed Consent: Written informed consent was obtained from the participants who participated in the study.

Peer-review: Externally peer-reviewed.

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Declaration of Interests: The authors declare that they have no competing interest.

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