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Auditory influence on postural control during stance tasks in different acoustic conditions

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Abstract.
BACKGROUND: Postural stability might be influenced by auditory input as humans utilize spatiotemporal information to localise sound sources. Earlier studies investigated the acoustic influence on posture but unfortunately experimental setup, room acoustics and conditions of participants varied widely.
OBJECTIVE: This study aimed at recording body sway velocity under clearly defined acoustic conditions in a homogenous group of young healthy participants.
METHODS: Thirty participants performed five stance tasks (standing eyes open/closed, standing on a foam support eyes open/closed, Tandem Romberg test eyes closed) under four acoustic conditions (in quiet, with a loudspeaker presenting continuous/interrupted noise, with ear protectors) in two different rooms (long/short reverberation time). Body sway velocity was determined close to body's centre of gravity.
RESULTS: Postural stability decreased significantly when continuous noise was applied and increased significantly when interrupted noise was presented in the reverberant room. The usage of ear protectors increased body sway velocity compared to quietness in both rooms.
CONCLUSIONS: An impaired auditory input by plugging/acoustic masking reduced postural control. Interrupted noise seems to provide a continuously repeated feedback about the postural position in a reverberant room. Hence, the effect of hearing on posture highly depends on the structure of the auditory signal, the sensorimotor condition and the acoustic environment.

Keywords: Auditory influence, mobile posturography, postural control, body sway, spatial cues

1. Introduction

Balance is mainly influenced by visual, proprioceptive and vestibular information [17]. Another sensory input to control balance might be hearing cues, such as time and level differences between both ears as humans use spatiotemporal features for orientation and localising sound sources [2, 13]. As yet, the relationship between acoustic cues and postural control for stance tasks was investigated. Observations from previous studies suggest a positive effect of sound on postural stability [3, 4, 14, 16, 18–20]. However, influencing factors such as age, gender, physiological conditions of the participants, room acoustics and experimental setup varied widely, whereby results were less consistent.

Besides differences in the recording method for postural changes (force platform, Nintendo Wii Balance Board, video system), the participant groups (healthy vs. hearing/vestibular impaired, sighted/blind, young/elder) and the acoustic input

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(broadband noise/pure tones/speech signal, ear protectors, number of sound sources, steady/rotating sound, loudspeaker/headphone) in previous studies, very limited information were given about the room properties (e.g. reverberation times, background noise). Though, these room properties as well as the presented stimulus and the position of sound source(s) and listener(s) in the room influence the localisation ability and therefore the orientation in a room [5, 6, 15]. The precedence effect is decisively for localisation [12]. This effect implies that the listeners' localisation depends on the localisation of the first arriving sound. Other sound, such as reflections, following the first arriving sound with a short time delay, gives weak information about the localisation of the sound source. Localisation in an absorbing room is significantly better than in a reflecting room [5, 6]. The localisation of static sound sources in the room could influence altered body sway upon changing auditory input. Hence, the auditory input should be clearly defined and include spatial conditions. Therefore, in our present study, reverberation time and background noise were precisely measured. Moreover, this study used the method of direct measurement of posture close to the body's centre of gravity.

The aim of this study was therefore to verify to what extends auditory input and spatial cues have an influence on postural control during stance under clearly defined acoustic conditions in a homogenous group of young healthy participants.

2. Material and methods

2.1. Subjects

A total of 30 healthy subjects (18 females and 12 males, mean age = 25 years, range = 16–38 years) participated in this study. All participants had normal hearing in pure tone audiometry at 0.25, 0.5, 1, 2, 4, 6 and 8 kHz (ISO 7029:2000 [8], 0.1 percentile) and normal or corrected visual acuity of at least 0.7 (decimal, tested with Landolt rings). Furthermore, the peripheral vestibular system was examined. Otolith organs (sacculus and utriculus) were tested by cervical vestibular evoked myogenic potentials (cVEMP) with an ECLIPSE measurement system (Interacoustics, Denmark) and subjective haptic vertical (SHV) with a screening tablet (Zeisberg GmbH, Reutlingen, Germany), respectively. Anterior, posterior and horizontal semicircular canals were investigated by the video head impulse test (vHIT) system Eyeseecam (Otometrics, Denmark). All participants showed normal results in the above-mentioned tests. Specific tests for central vestibular disorders were not performed. The postural stability in stance and gait tasks was determined with the VertiGuard system (Zeisberg GmbH, Reutlingen, Germany) by the Standard Balance Deficit Test (SBDT) [1]. The composite score of the SBDT ranges from 0 to 100 with the higher value for the greater instability. Only subjects who showed a composite score in the normal limit of up to 50 were included in the study. All participants indicated no subjective vertigo which was queried by the Dizziness Handicap Inventory (DHI) [9]. Additionally, all participants had no history of dizziness or balance problems. Participants with acute or chronic abnormal organ function, including cardiovascular diseases and neurological diseases (e.g. depression, anxiety, addiction), an orthopaedic malposition of the feet and participants taking medication which influence the postural control (e.g. sedating drugs) were excluded from this study. The Institutional Review Board (University of Berlin) approved the study protocol. All experiments were carried out in accordance with the Declaration of Helsinki and informed consent was obtained from all participants.

2.2. Room properties

For the investigation participants performed five standing tasks under four acoustic conditions in two rooms, one room with a short reverberation time (T30 (125–8000 Hz) = 0.32-0.16 s) (SR) and the other one with a long reverberation time (T30 (125–8000 Hz) = 2.46-1.05 s) (LR). Reverberation time was measured with the integrated impulse response method (ISO 3382-1:2009 [7]) at several different positions in the rooms. This was almost independent from spatial position. Both rooms were monitored by a calibrated sound level recording system to ensure an ambient noise level of below 40 dB SPL during the task performance.

2.3. Procedure and setup

The performed standing tasks included:

- standing on two legs with eyes open/closed,
- standing on two legs on a foam support with eyes open/closed
- and Tandem Romberg test with eyes closed (heel-to-toe position and arms crossed above shoulders) [11]

During performance participants wore similar disposable socks to diminish the influence of different personal shoes on sway measures. The distance between the feet was the width of participant's fist. To ensure a similar distance for each measurement and a similar position, marks were used. All standing tasks were recorded 20 s 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)
- and participants wore earplugs (Howard Leight Max) and additionally circumaural ear protectors (Moldex M1) (EP).

The loudspeaker (JBL Control One) was placed 1 m in room SR and 2 m in room LR in front of the participant. Both stimuli, continuous and interrupted noise, consisted of white broadband noise with a frequency range of 80 Hz-20 kHz as this is the frequency range of the loudspeaker (±3 dB) in which the transmission is almost linear. For the interrupted noise condition, noise and pause alternated every 0.5 s. Noise was presented at 60 dB SPL at participant position for task performances. The distances were different because of spatial conditions in the rooms. Acoustic insulation value of earplugs combined with circumaural ear protectors for white broadband noise amounted 45 dB over all frequencies. In order to avoid a different performance by different light irradiation through the windows in the rooms, all windows were darkened and artificial light of similar amount was applied by four evenly distributed ceiling lights to illuminate the different rooms.

Body sway velocity during the stance tasks was measured with the VertiGuard system (Zeisberg GmbH, Reutlingen, Germany). This device records the momentary angular velocity ω [°/s] of trunk movements with a sampling frequency of 80 Hz in anterior-posterior and medial-lateral direction at the hip (close to body's centre of gravity). The lower the angular velocity the less fast body sways and the better is the postural stability. The order of all tasks (e.g. standing on two legs with eyes open) and all acoustic conditions (e.g. earplugs and additionally circumaural ear protectors) as well as the examination rooms (e.g. short reverberation time) was randomised for the measurement schedule using MATLAB R2014b. All performances were visually and acoustically recorded and analysed offline for a subsequent verification of unwanted background noise or incorrectly performed task.

The first and the last second of the recordings were not included in the analysis as possible changes of body sway caused by switching on and off the sound sources should be avoided, so that in total 18 s remained. Furthermore, median from the absolute values of angular velocities were calculated for a statistical comparison between condition R and conditions cN, iN or EP. The values of angular velocities [°/s] were very small, wherefore differences between two conditions were given in percentage by determining the mean value of condition R as 100 %. The performance of the experiment was online and offline precisely controlled and moreover, the group of participants was very homogenous as all participants had to meet the including criterions. Hence, extreme values (1.5 times smaller or greater than the interquartile range) were considered as measurement errors and were removed from the further analysis. In total, only 5.3 % of the data were calculated as extreme values.

2.4. Statistical analysis

For each task, the reference condition (silence) was compared with both noise conditions and with the condition where participants wore ear protectors (*t*-test for dependent samples or Wilcoxon test (depending on data distribution)). Gender-related differences were determined by applying a *t*-test for independent samples or Mann-Whitney test depending on the data distribution. Data distribution was tested by the Kolmogorov-Smirnov test. A significance level of $p < 0.05$ was applied for all statistical testing. The p value was corrected by the Bonferroni method as multiple comparisons were performed.

3. Results

3.1. Gender-specific analysis

A significant change between female and male volunteers could be observed only between the reference condition and the EP condition during standing with eyes open (medial-lateral direction) in room LR ($p = 0.012$). The difference between these both conditions for males was on average –0.02 [°/s] and for females +0.05 [°/s]. The sign indicates a reduced (–) or an increased (+) angular velocity by wearing ear protectors compared to the reference. However, only the female participants showed for this task a

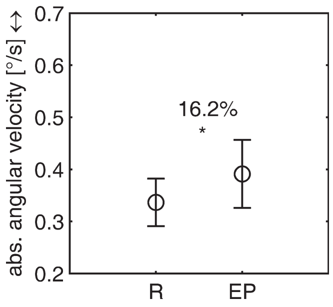

Fig. 1. Significant changes of body sway velocity (median) for standing on two legs with eyes open in medial-lateral direction between reference condition (R) and condition participants wore ear protectors (EP) in the room with a long reverberation time (LR) for female participants. Standard deviation is additionally shown. The percentage deviation of body sway velocity of condition EP from condition R was calculated by determining the mean value of condition R as 100 %.

significantly higher ($p = 0.011$; 16.2 %) sway velocity when wearing ear protectors compared to reference condition (Fig. 1), whereas there was no significant difference between these both conditions for male participants.

3.2. *Reference condition vs. noise/ear protectors in a room with a long reverberation time*

For each task and sway direction the reference condition was compared with conditions iN, cN and EP (Table 1). In total, six comparisons showed statistically significant differences (Fig. 2). The comparison between the reference condition and the condition iN showed a significant lower sway velocity (–10.5 %, $p = 0.007$) for standing on two legs on a foam support with eyes closed in medial-lateral direction (Fig. 2a). However, body sway velocity increased in the condition with continuously presented noise during standing on two legs with eyes open in medial-lateral and anterior-posterior direction (26.8 %, $p = 0.009$ or 24.2%, $p = 0.001$, respectively) (Fig. 2b and c). The same holds true for standing on two legs with eyes closed in medial-lateral direction (19.7 %, $p = 0.004$) (Fig. 2d).

Sway velocity also increased in medial-lateral direction when participants wore ear protectors during standing on two legs with eyes closed (13.8 %, $p = 0.009$) (Fig. 2e) and on a foam support with eyes open in anterior-posterior direction (9.2 %, $p = 0.015$) (Fig. 2f). In essence, interrupted noise led to a decrease in sway velocity, whereas continuous noise and wearing ear protectors caused an increased sway velocity compared to the reference condition.

3.3. *Reference condition vs. noise/ear protectors in a room with a short reverberation time*

In total, three of 30 investigated conditions showed statistically significant differences compared to the reference condition (Table 2). Figure 3 shows all significant changes. Participants swayed significantly (9.2 %, $p = 0.013$) faster during standing with eyes closed (anterior-posterior direction) (Fig. 3a) as well as during standing on a foam support with eyes open and eyes closed (15.2 %, $p = 0.01$ or 8.9 %, $p = 0.008$) in medial-lateral direction (Fig. 3b, c) when wearing ear protectors compared to the reference condition.

Table 1

Mean absolute angular velocities [°/s] and the standard deviations (italic) of all participants are shown for the tasks in the room with a long reverberation time. Arrows indicate medial-lateral (↔) and anterior-posterior (↕) direction. The reference condition (R) was compared with presented continuous (cN) or interrupted (iN) noise and wearing ear protectors (EP). A *t*-test for dependent samples or Wilcoxon test was applied. The symbol ♀ indicates significance only for female participants

Standing on two legs with eyes open				Standing on two legs with eyes closed				Standing on two legs on a foam support with eyes open				Standing on two legs on a foam support with eyes closed				Tandem Romberg test with eyes closed			
↔		↕		↔		↕		↔		↕		↔		↕		↔		↕	
R – cN**		**R – cN****		**R – cN****		**R – cN**		**R – cN**		**R – cN**		**R – cN**		**R – cN**		**R – cN**		**R – cN**	
0.32	0.40	0.24	0.30	0.33	0.39	0.28	0.29	0.41	0.44	0.29	0.29	0.57	0.57	0.44	0.42	0.75	0.74	0.51	0.54
0.10	*0.17*	*0.08*	*0.10*	*0.12*	*0.11*	*0.10*	*0.09*	*0.10*	*0.13*	*0.07*	*0.07*	*0.17*	*0.15*	*0.10*	*0.09*	*0.26*	*0.25*	*0.18*	*0.14*
R – iN		**R – iN**		**R – iN**		**R – iN**		**R – iN**		**R – iN**		**R – iN****		**R – iN**		**R – iN**		**R – iN**	
0.32	0.33	0.25	0.27	0.33	0.33	0.27	0.28	0.40	0.43	0.30	0.32	0.57	0.51	0.43	0.45	0.72	0.72	0.48	0.50
0.10	*0.12*	*0.08*	*0.09*	*0.12*	*0.11*	*0.09*	*0.08*	*0.10*	*0.16*	*0.07*	*0.11*	*0.17*	*0.13*	*0.08*	*0.10*	*0.23*	*0.24*	*0.10*	*0.11*
R – EP*♀		**R – EP**		**R – EP****		**R – EP**		**R – EP**		**R – EP***		**R – EP**		**R – EP**		**R – EP**		**R – EP**	
0.32	0.35	0.24	0.26	0.29	0.33	0.27	0.29	0.41	0.44	0.30	0.32	0.57	0.57	0.44	0.45	0.75	0.71	0.50	0.51
0.09	*0.13*	*0.08*	*0.10*	*0.08*	*0.10*	*0.09*	*0.09*	*0.10*	*0.13*	*0.07*	*0.10*	*0.17*	*0.15*	*0.10*	*0.11*	*0.25*	*0.22*	*0.12*	*0.14*

Significant level: * ($p < 0.05$), ** ($p < 0.01$) or *** ($p < 0.001$). *P* value was corrected by the Bonferroni method.

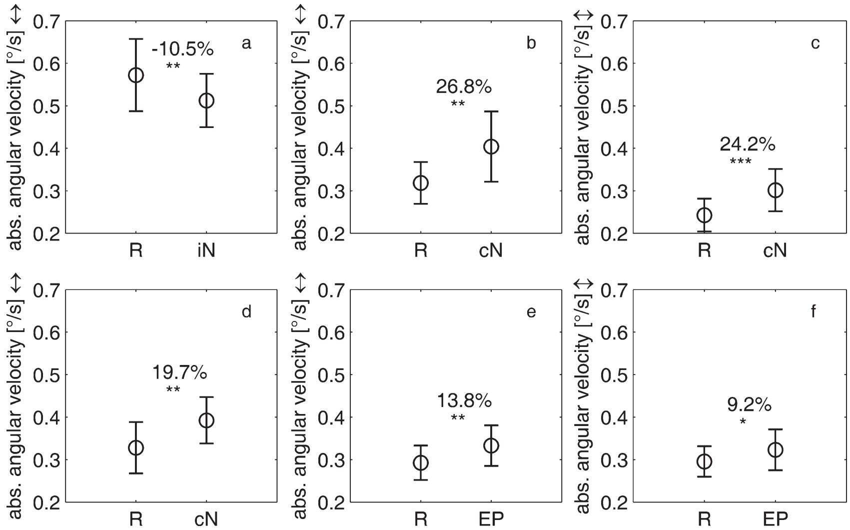

Fig. 2. Significant changes of body sway velocity (median) for standing on two legs on a foam support eyes closed (a), standing on two legs eyes open (b, c), standing on two legs eyes closed (d, e) and standing on two legs on a foam support eyes open (f) in medial-lateral or anterior-posterior direction between reference condition (R) and condition where continuous (cN) or interrupted white noise (iN) were presented and condition participants wore ear protectors (EP) in the room with a long reverberation time (LR). Standard deviation is additionally shown. The percentage deviations of body sway velocity of conditions iN, cN and EP from condition R were calculated by determining the mean value of condition R as 100 %.

Table 2

Mean absolute angular velocities [°/s] and the standard deviations (italic) of all participants are shown for the tasks in the room with a short reverberation time. Arrows indicate medial-lateral (↔) and anterior-posterior (↕) direction. The reference condition (R) was compared with presented continuous (cN) or interrupted (iN) noise and wearing ear protectors (EP). A *t*-test for dependent samples or Wilcoxon test was applied

Standing on two legs with eyes open				Standing on two legs with eyes closed				Standing on two legs on a foam support with eyes open				Standing on two legs on a foam support with eyes closed				Tandem Romberg test with eyes closed			
↔		↕		↔		↕		↔		↕		↔		↕		↔		↕	
R – cN		**R – cN**		**R – cN**		**R – cN**		**R – cN**		**R – cN**		**R – cN**		**R – cN**		**R – cN**		**R – cN**	
0.34	0.32	0.25	0.24	0.33	0.34	0.28	0.26	0.37	0.41	0.28	0.29	0.52	0.55	0.43	0.42	0.79	0.83	0.52	0.53
0.13	*0.10*	*0.09*	*0.08*	*0.10*	*0.10*	*0.09*	*0.07*	*0.12*	*0.15*	*0.09*	*0.08*	*0.16*	*0.16*	*0.09*	*0.10*	*0.29*	*0.37*	*0.14*	*0.16*
R – iN		**R – iN**		**R – iN**		**R – iN**		**R – iN**		**R – iN**		**R – iN**		**R – iN**		**R – iN**		**R – iN**	
0.34	0.33	0.25	0.25	0.35	0.35	0.28	0.28	0.37	0.39	0.27	0.29	0.51	0.51	0.43	0.42	0.76	0.86	0.52	0.58
0.13	*0.09*	*0.09*	*0.08*	*0.14*	*0.12*	*0.09*	*0.09*	*0.12*	*0.13*	*0.08*	*0.08*	*0.15*	*0.15*	*0.09*	*0.10*	*0.25*	*0.45*	*0.14*	*0.27*
R – EP		**R – EP**		**R – EP**		**R – EP***		**R – EP***		**R – EP**		**R – EP****		**R – EP**		**R – EP**		**R – EP**	
0.33	0.33	0.25	0.28	0.33	0.33	0.27	0.30	0.36	0.42	0.28	0.29	0.50	0.54	0.42	0.44	0.76	0.70	0.54	0.56
0.12	*0.12*	*0.09*	*0.11*	*0.10*	*0.11*	*0.08*	*0.09*	*0.12*	*0.13*	*0.09*	*0.08*	*0.14*	*0.14*	*0.09*	*0.11*	*0.25*	*0.21*	*0.16*	*0.19*

Significant level: *($p < 0.05$), **($p < 0.01$) or ***($p < 0.001$). *P* value was corrected by the Bonferroni method.

The conditions iN and cN caused no significant changes in body sway velocity. Furthermore, in both rooms no influence on sway velocity was detected by changing any acoustical condition during Tandem Romberg test.

4. Discussion

The present study showed that under well-defined experimental conditions interrupted noise presented in front caused a reduction of body sway velocity compared to reference condition, whereas continuous noise and ear protectors increased sway velocity in some conditions. Interestingly, in room SR only ear protectors changed significantly body sway velocity. It is also important to notice, that significant changes of sway velocity caused by different acoustic conditions were not observed for all tasks. This holds true especially for the most difficult task, the Tandem Romberg test. In previous studies, postural stability

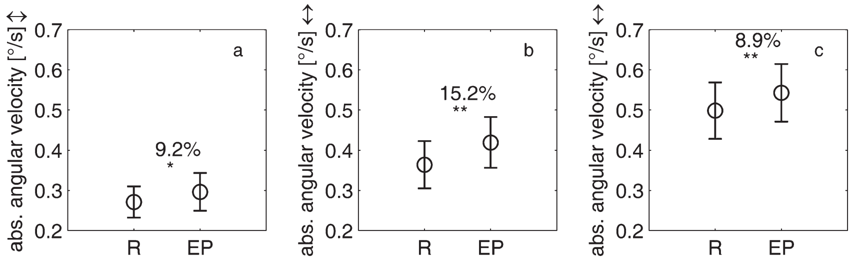

Fig. 3. Significant changes of body sway velocity (median) for standing on two legs eyes closed (a), standing on two legs on a foam support eyes open (b) and standing on two legs on a foam support eyes closed (c) in medial-lateral or anterior-posterior direction between reference condition (R) and condition participants wore ear protectors (EP) in the room with a short reverberation time (SR). Standard deviation is additionally shown. The percentage deviations of body sway velocity of condition EP from condition R were calculated by determining the mean value of condition R as 100 %.

during the Tandem Romberg test was increased during the application of continuous white noise from the front [20]. Vitkovic et al. [19] also reported an improved postural stability for standing tasks (eyes open/closed on a firm/foam surface) when stationary or moving white noise was added compared to silence or earplug conditions. However, in the present study postural control was investigated by measuring angular velocities close to the body's centre of gravity and not by recording the ground reaction forces with a force platform or Nintendo Wii Balance Board as this was done in most previous studies [3, 4, 10, 16, 18, 19]. The correlation between these both measurement methods was not investigated. Thus, our data are difficult to compare with other data. Moreover, the present results showed that during more complex tasks the hierarchic higher inputs (proprioceptive and vestibular) play the key role for maintaining postural control.

4.1. Gender-specific analysis

The gender-specific analysis indicates that changes in body sway velocity caused by changing the acoustic settings are only slightly influenced by gender. Just in one of 60 tested conditions, the influence of an acoustic input on postural control differed between female and male subjects. Only females performed worse for standing with open eyes in the hallway with ear protectors vs. reference condition. Females seem to use acoustic reflections even for the simplest task to maintain balance, whereas males use them only in challenging situations (e.g. if there is limited input from the visual or proprioceptive system).

4.2. Spatial influence on balance control

Even if the method of body sway measurement applied in the present study differed from previous studies there are some similarities of the results. Kanegaonkar et al. [10] observed a decreased postural stability in a sound-limited environment when participants wore ear protectors vs. wore no ear protectors. In the present study, participants showed as well in some conditions higher body sway velocities with ear protectors in both rooms. It is important to mention, that the sound-limited environment from Kanegaonkar's study [10] was a standard audiology booth and therefore only a semi-anechoic room. Additionally, the used hardware in this room produced some low-level background noise. In the present study, body sway velocity was increased when continuous white noise was presented and body sway velocity was decreased when interrupted white noise was played in the room with a long reverberation time (T30 (125–8000 Hz) = 2.46-1.05 s). Assuming that spatial reflections cannot be perceived with ear protectors or upon presenting continuous noise directly from the front, these findings suggest that reflections play an important role in controlling posture. In the room with a short reverberation time (T30 (125–8000 Hz) = 0.32-0.16 s), additional noise did not influence body sway velocity as it was observed in the room with a long reverberation time. Possibly, interrupted noise which reduced body sway velocity in the room with a long reverberation time, does not generate additional, for the participant perceivable, reflections when the reverberation time is very short. In the room with long reverberation time, reflections could be clearly perceived during the breaks of 0.5 s of interrupted noise which probably provided a benefit for postural control. Continuous noise masked required spatial reflections to stabilise body sway in the room with a long reverberation time, but not in the anechoic room.

Different factors such as room acoustics, the presented stimulus and the position of sound source(s) and listener(s) in the room change the ability to localise static sound sources in rooms [5, 6, 15]. As the group of participants in this study was homogenous and all participants showed normal hearing, influencing factors such as hearing loss and further physiological conditions did not play a role. For continuous broadband noise and one third octave noise bands, localisation ability in rooms depends on the reverberation time [5, 6]. In a reflecting room the localisation was significantly worse than in an absorbing room. Decisive for the localisation ability is the precedence effect [12]. The listeners' localisation is determined by the localisation of the first arriving sound. By contrast, sounds, such as reflections, that directly follow the first arriving sound have a very small influence on the localisation of the sound source. For the present study, localisation ability is likely worse in room (LR) and better in room (SR). In both rooms, localisation is impaired with hearing protectors and therefore, postural stability was decreased. The low-level background noise in room (SR) might already improve postural control as there were no significant differences when additional noise was presented. In room (LR), continuously presented noise impaired postural control, whereas interrupted noise improved it. Continuous noise is very difficult to localise in a reverberant room as participants perceived the first sound wave just once when noise was switched on. During the presentation of the stimulus, reverberant noise affected the ability to localise the sound source. However, participants received the first sound wave with interrupted noise more often which might improve the localisation ability and therefore the postural stability. The low-level background noise in silent condition seemed to improve postural stability to a certain extent as body sway velocity was increased by applying hearing protectors.

The effect sizes of the significant results in this study showed for almost all cases a large effect size (0.51 to 0.95) and for one condition (standing on two legs on a foam support with eyes open) a medium effect size (0.32). Hence, the acoustic environment has an impact on postural stability and should be therefore defined during balance measurements. For clinical routine a normal examination room should be used. Such a room is not free of reflections, so the patients balance performance do not suffer from lack of reflections. Furthermore, in these rooms are usually no instruments generating permanent noise at a sound level which could mask the reflections in the rooms. In previous studies and in this study, different sounds were presented from a fixed sound source that improved postural stability. However, for clinical routine, an optimal sound condition cannot be recommended as the kind of the auditory signal and the room acoustic play an important role. Nevertheless, it can be recommended that during balance measurements the acoustic environment should be kept as constant as possible and sudden changes of the acoustic environment should be avoided (e.g. audiologist starts talking, telephone ringing). Furthermore, for comparative measurements (e.g. before and after a balance therapy), the acoustic environment should be almost the same in all sessions.

In essence, the present study proved a clear physiological influence of the acoustic input on postural control during stance tasks in young healthy participants. However, the influence highly depends on the structure of the auditory signal, the sensorimotor condition and the acoustic environment.

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