



Research article

Auditory noise improves balance control by cross-modal stochastic resonance



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ABSTRACT

It is known that enhanced somatosensory function leads to improved balance, and somatosensory function can be enhanced by the appropriate level of mechanical, visual, or auditory noise. In this study, we tested the potential benefit of an auditory noise on balance control. We first assessed static balance by measuring 10 times the duration of standing on the toes of one leg with closed eyes. For the 18 healthy adult participants, the median standing times ranged from 2.1 to 45.6 s, and the median of the distribution was 9.9 s. From the above, the participants were divided into two groups: lower (below 10 s, $n = 9$) and higher (above 10 s, $n = 9$) balance groups. We then investigated the effect on balance control of an auditory white noise emitted at the detection threshold. Each individual performed 20 trials. The auditory noise was applied in half the trials, while the remaining trials were conducted without noise. The order of the noise and no-noise trials was quasi-random. In the lower-balance group, the median standing time significantly increased during the noise trials (10.3 s) compared with the time in the no-noise controls (5.2 s). On the other hand, noise had no significant effect in the higher-balance group, presumably because of a ceiling effect. These findings suggest that static balance in the lower-balance participants can be improved by applying a weak noise through cross-modal stochastic resonance.

1. Introduction

The enhanced balance control is important and useful not only for the elderly but also for young adults as decrease of balance ability increases the risk of falling and broken bone. Balance control is based on sensory inputs from the visual, somatosensory, and vestibular systems [1, 2, 3]. Recently, several studies have shown that auditory inputs reduce postural sway primarily when projected through speakers. Although the precise mechanism involved is not known, the auditory cues might serve as an auditory anchor for balance [4, 5, 6].

Another approach to improve balance is the use of stochastic resonance (SR). SR is the phenomenon wherein a weak noise enhances the detection of a subthreshold signal in nonlinear systems [7]. SR has been widely examined in physical [8] and biological systems [9, 10], including in human sensory systems. It might contribute in improving signal detection in the visual, auditory, and somatosensory systems [11, 12, 13]. The detection of subthreshold and suprathreshold visual signals can be improved by the addition of a visual noise [14]. The auditory signal

detection is enhanced by adding an auditory noise in healthy adults and humans with cochlear implants [15, 16]. In the somatosensory system, input noise can restore the reduction in tactile sensitivity caused by aging [17], stroke, or diabetic neuropathy [18]. It has also been shown that mechanical or electrical noise applied at the skin surface enhances somatosensory function in healthy young participants [19, 20]. In addition, when noise was applied to the skin at the feet or knees, balance was improved [21, 22]. Moreover, it was recently found that an auditory noise enhanced the sensory processing in the visual and somatosensory systems, as well as the hands' motor performance, via cross-modal SR [23, 24, 25, 26]. From these findings, we hypothesized that an auditory noise can improve balance control by SR, because enhanced sensitivity of the visual and somatosensory systems should lead to improvement of balance control. In the present study, two experiments were performed to test this hypothesis. In the first experiment, we examined the baseline distribution of static balance ability. In the second experiment, we investigated whether static balance is improved by a weak auditory noise.

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2. Materials and methods

2.1. Experiment 1

2.1.1. Participants

The experimental group was composed of 18 healthy vocational college students, 13 males and 5 females (mean age \pm SD, 26.2 ± 8.9 years). Ethical approval was obtained from the Vocational College of Osaka Judo Therapist Association ethics committee. All the procedures complied with the Helsinki declaration (1975). Informed consent was obtained from all individual participants.

2.1.2. Apparatus and procedures

Static balance ability was assessed by measuring the duration of standing on the toes of one foot with the eyes closed. Participants stood facing forward on a balance board (Wii Fit® platform, Nintendo, Japan) in an experimental room ventilated and maintained at constant temperature (21 °C). We used the balance board to control the standing position. It also allowed to keep the feedback information from the somatosensory system and the repulsive force from the floor as constant as possible. Arms were crossed on the chest with hands resting on shoulders. The supporting leg (non-preferred leg) was chosen by the participant. The non-supporting leg was held forward with the hip and knee joints bent at a 90-degree angle. The standing duration was measured using a stopwatch. The measurements were repeated 10 times with an intertrial interval of 5–15 s. The median standing time was calculated for each individual. The trial arbitrarily started as decided by the participant and was terminated when one of the following happened: a hand left the shoulder, the supporting leg left the original position, or the non-supporting leg touched the board or floor. The upper time limit was set at 60 s. If standing time reached the upper limit, the trial was broken off.

2.1.3. Data analysis

Participants were divided into two groups (lower-and higher-balance groups) according to the median of standing time distribution. The cut-off was chosen based on a data-driven method. The non-parametric statistical analysis was used for standing time because it can be applied independent of the distribution normality. The median of 10 standing times was calculated for each participant and difference between the medians was analyzed using the Mann–Whitney U-test. The effect size for the U-test (r) was obtained by dividing Z by square root of n . All statistics were computed in R (The R Foundation for Statistical Computing Platform, version 2.14.1) or Statacel (version 4).

2.2. Experiment 2

2.2.1. Participants

The same 18 volunteers recruited in the first experiment participated in this experiment. Ethical approval, procedures, and informed consents were the same as described in Experiment 1.

2.2.2. Apparatus and procedures

The auditory white noise generated by a computer was binaurally presented to the participants through Bluetooth earphones (Truengine 3SE, Soundpeats, China). The background noise level was 41 dB (sound pressure level (SPL)) as measured using a sound level meter at C-scale (Rion, NA-20, Japan). The noise intensity was set to the detection threshold of each participant. The noise threshold was measured using the psychophysical method of limits [18, 27, 28, 29].

Standing time was measured 20 times. Noise was applied in half of the trials, while the remaining trials were performed without noise. The order of the noise and no-noise trials was quasi-random to exclude the possibility that the experimental results are affected by changes in arousal or attention. The rest of the procedure was the same as in the first experiment.

2.2.3. Data analysis

Difference in the auditory threshold intensities between the lower- and higher-balance groups was analyzed using Mann–Whitney U-test. Replicability of the measurement of standing times was analyzed using Spearman's correlation coefficient by rank test between standing times in the first and the second experiments. Difference between standing times during noise and no-noise trials was analyzed using the Mann–Whitney U-test both in the lower- and higher-balance groups. The effect of noise addition on standing time was calculated by subtracting standing time during the no-noise control trial from the time measured in the trials with noise in the 18 participants. Relation between the effects of noise and the control standing time was analyzed using the Spearman's correlation coefficient by rank test.

3. Results

3.1. Experiment 1

The variability of standing time between subjects was relatively large. The standing time upper limit was reached in 3 out of 180 trials, twice by the same participant. The median standing times of the 18 individuals ranged from 2.1 to 45.6 s. Figure 1 shows a histogram of standing times with a class interval of 10 s. The distribution had a long right tail, and the skewness was 1.12. The median standing time for all participants was 9.9 s. From these data, we divided the 18 participants into two groups: lower (standing time below 10 s, $n = 9$) and higher (standing time above 10 s, $n = 9$) balance groups. The median standing time was 4.5 s in the lower-balance group and 23.0 s in the higher-balance group. The difference between the median standing times of the lower- and higher-balance groups was statistically significant (Mann–Whitney U-test, $Z = 3.576$, $p = 0.0003$, $r = 0.843$).

3.2. Experiment 2

Auditory noise threshold was measured for each individual. The mean threshold intensity was 47.2 ± 0.22 dB (SPL, mean \pm SE) for all 18 participants, 47.4 ± 0.22 dB (mean \pm SE) for the lower-balance group, and 47.0 ± 0.21 dB (mean \pm SE) for the higher-balance group. No significant difference was found in the threshold between the lower- and higher-balance groups (Mann–Whitney U-test, $Z = 0.309$, NS, $r = 0.073$).

Figure 2 shows the correlation between standing times in the first experiment and in the trials without noise of the second experiment. The Spearman's rank correlation coefficient was 0.771.

Figure 3A shows the median standing time measured in the trials with or without noise for each individual in the lower-balance group. Standing times of the nine participants increased when auditory noise was applied. In the higher-balance group, standing time was increased by noise in only two out of nine participants (Figure 3B). During the trials without noise, one of these two participants had a median standing time below 10 s, which was the limit between the lower- and higher-balance groups.

The median standing times during the trials with or without noise are displayed in Figure 4. In the lower-balance group, the median standing time was 5.2 s in the no-noise trials and reached 10.3 s in the trials with noise. The statistical analysis using the Mann–Whitney U-test revealed that standing time significantly increased during the trials with noise compared with the no-noise ones ($Z = 2.782$, $p = 0.005$, $r = 0.656$). In the higher-balance group, the median standing time was 21.0 s for the measurements without noise and 20.5 s for the trials with noise. The difference between standing times in the trials with and without noise was not significant (Mann–Whitney U-test, $Z = 0.530$, NS, $r = 0.125$).

Static balance in the lower-balance group was improved by the addition of an auditory noise, while no significant effects were found in the higher-balance group. To elucidate the different effects of SR on the lower- and higher-balance groups, the effect of noise addition was calculated by subtracting standing time in no-noise trial from the one in noise trial for each participant. The Spearman's correlation coefficient

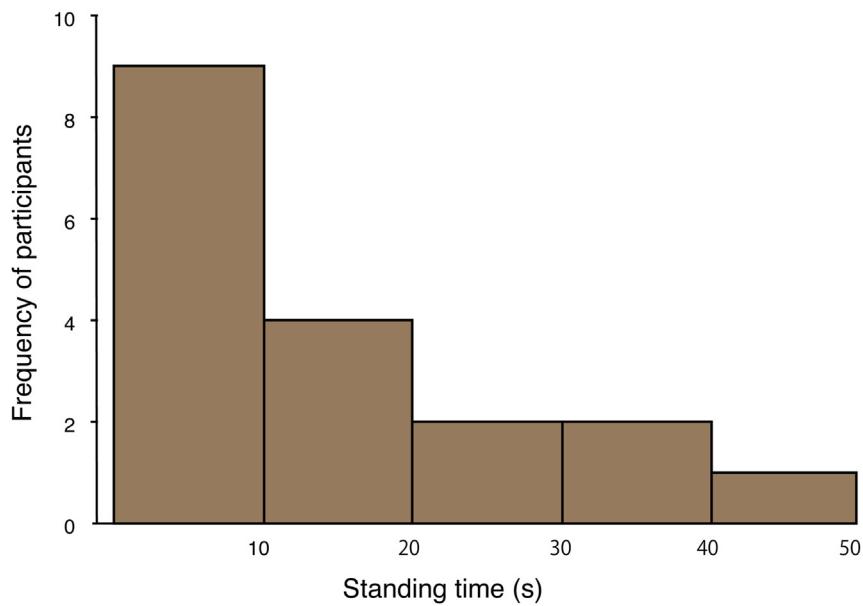


Figure 1. Histogram of standing times for the 18 participants. The class interval is 10 s.

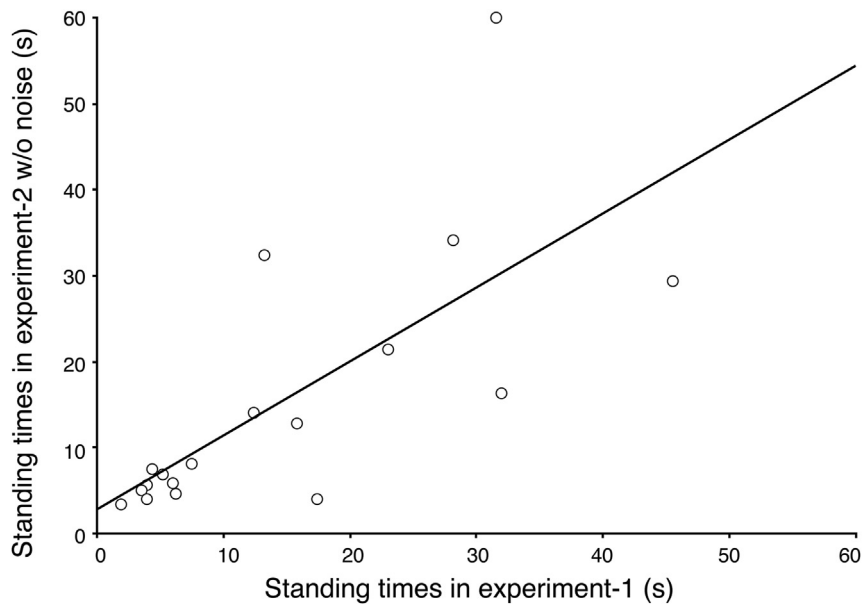


Figure 2. Correlation between standing times measured in the first experiment and in the trials without noise of the second experiment for the same individuals. The diagonal line represents the regression line. The Spearman's correlation coefficient was 0.771.

between the effect of noise and standing times in no-noise trials was -0.598 (Figure 5).

4. Discussion

In this study, we tested the hypothesis that a weak auditory noise can improve balance control via cross-modal SR in healthy young adults. In the first experiment, we examined the baseline distribution of the static balance by measuring standing times. In the second experiment, we investigated whether the static balance was improved by adding an auditory noise of weak intensity. Standing times significantly increased in presence of the noise in the lower-balance group.

The validity of the methods was checked by the following three points. First, the factors influencing static balance include height, weight, gender, muscle power, and task difficulty. If task difficulty is low, many

healthy young adults are expected to reach the upper limit time. Task difficulty can be efficiently increased by reducing the area of the base of support and by visual restriction [30, 31]. In the present study, only a few participants (2 out of 18, 11.1%) reached to the upper limit. This shows that the task was very challenging, and we should keep in mind that only the lower-balance participants, and not the low-balance patients, were included in the present study. Second, standing times in the trials of the first experiment are correlated with those in the trials without noise of the second experiment. This finding is consistent with a previous report that showed low within-subject variability [32]. Third, in this study, we measured standing time, which seems less precise compared with the center of mass or pressure. Nevertheless, we showed significant effects of noise on balance control in the lower-balance participants. This suggests that the effects of auditory noise on static balance are definite and profound, at least in the lower-balance participants.

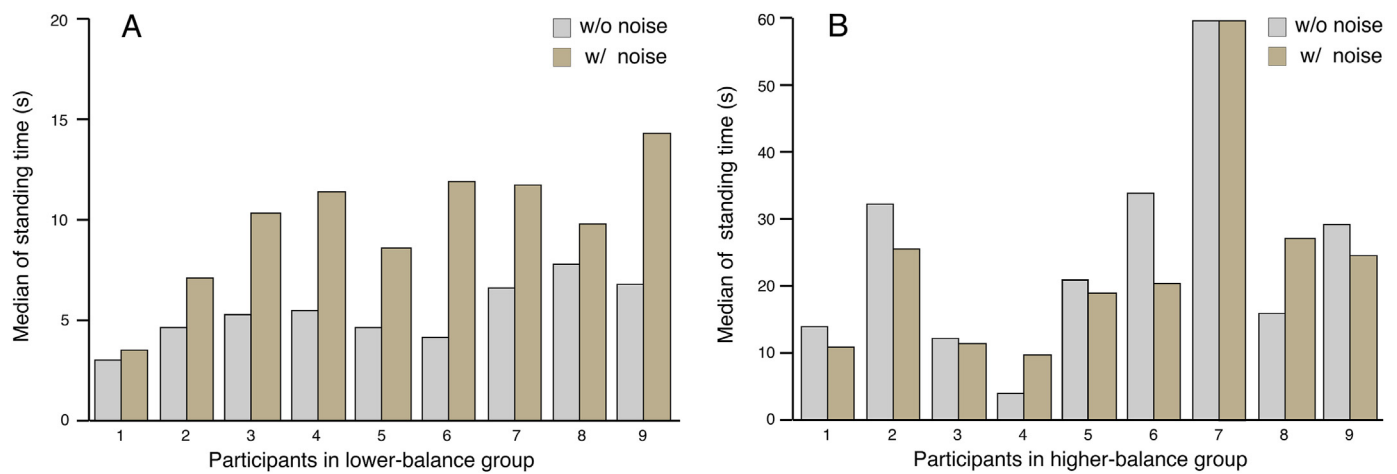


Figure 3. Standing times measured with or without auditory noise in each individual in the lower-balance (A) and the higher-balance (B) groups.

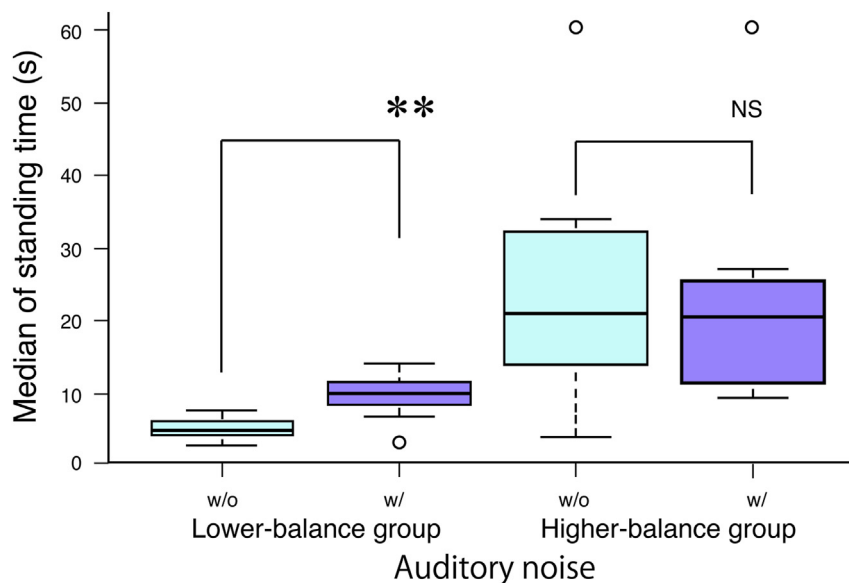


Figure 4. Changes in standing times by applying the auditory noise in lower- and higher-balance groups. Standing times measured with (w/) or without (w/o) auditory noise are displayed as box plots with the hinges of the box representing the 25% and 75% interquartile ranges. The line in the box indicates the median, and the whiskers provide the upper and lower quartile ± 1.5 times the interquartile range. The open circles represent outliers. $**p < 0.01$ and NS, not significant.

A subthreshold signal can be detected if the near-threshold level of noise is applied to the human sensory systems [12, 28, 33]. In the somatosensory system, a subthreshold tactile stimulus became detectable if a weak mechanical noise was simultaneously applied in healthy participants [34, 35]. In addition, a positive correlation between somatosensory perception and the ability to control balance has been reported. The improvement of somatosensory function is effective in reducing the postural sway through SR mechanism [19, 21, 22]. In most SR studies, both signal and noise are from the same modality. However, a type of SR, known as cross-modal SR, can occur using different modalities for signal and noise [23, 36]. For example, applying visual noise improved somatosensory perception [37]. The presentation of auditory noise enhanced tactile, visual, and proprioceptive sensations [25, 26]. Auditory noise also improved the fine motor performance of the hand [24]. In the present study, we investigated whether an auditory noise enhanced balance control in healthy young adults. Static balance was improved by the addition of an auditory noise in the participants with lower-balance control (Figure 3A). Indeed, the median standing time for participants in the lower-balance group was significantly longer during the noise trials than it was during the no-noise trials (Figure 4). These findings are

consistent with previous studies reporting that auditory noise facilitated tactile, visual, and proprioceptive perceptions via SR [25, 26].

It has been reported that hearing perception is modified by two other major sensory systems: vision and somatosensation [38, 39]. This synthesis occurs at every level of the ascending auditory pathway from the cochlear nucleus to the auditory cortex [40, 41]. This convergence seems to be the neural correlate for audio-tactile SR [23]. As for the haptic modulation by audition, a multimodal neuron that responds to visual, auditory, and haptic cues has been found in the somatosensory cortex [42, 43], which might be the neural substrate for haptic-auditory SR [36].

Significant negative correlation was observed between the effect of noise and the control standing time (Figure 5). That is, the improvement of balance control provided by SR was less prominent in the higher-balance participants. These findings suggest that there was a ceiling effect in the higher-balance group as previously described in the supra-threshold SR paradigm for signal detection [14]. This may account for the lack of improved performance in the higher-balance group.

In our study, a weak auditory noise improved balance by SR; however, several studies conducted from a different perspective have shown

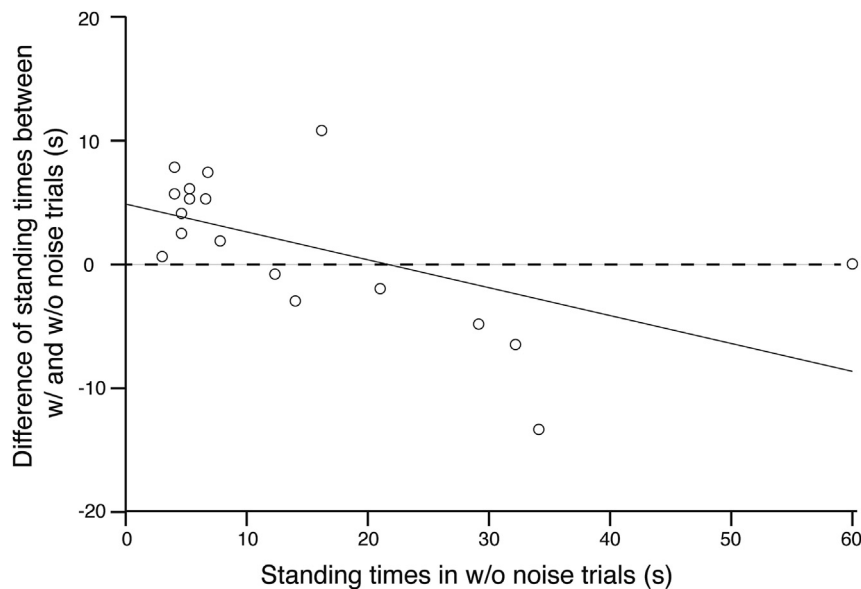


Figure 5. Correlation between standing times in no-noise (w/o) trials and differences in times measured during noise (w/) and no-noise (w/o) trials. The diagonal line represents the regression line. The Spearman's correlation coefficient was -0.598 .

improved balance with auditory inputs [6, 44, 45]. In these studies auditory inputs provided spatial orienting cues [4], and the mechanism of balance improvement is based on the hypothesis that a hearing map of our surroundings is used to maintain balance control [45]. However, SR is caused by the summation of signal and noise [11, 14, 35, 46]. In the present experiments, we used a weak noise near the detection level for each participant because the optimal noise intensity is located near the detection threshold level [33], although it can be tuned automatically based on sensor output autocorrelation [47], and it depends on the difficulty of the task [48]. In addition, we presented the auditory noise using earphones. These are unfavorable for the auditory anchor. Therefore, the present results suggest that enhanced balance control may be attributable to SR. Both somatosensory and visual feedback is important for balance control [1, 2, 3, 19]. Although the exact neural mechanisms involved in balance control improvement by SR are not known, it is probable that increased somatosensory and visual feedback information lead to better balance control. The present results suggest that sensory systems interact with each other leading to the integration of information from different sensory modalities [23, 36] and influencing the motor system [19, 24]. From these studies, it seems probable that auditory inputs might improve balance control by direct and indirect influences to the balance control system.

In conclusion, we investigated whether a weak auditory noise improved balance control in healthy young adults. To this aim, standing times with or without auditory noise were analyzed. Standing times were significantly increased by the addition of a weak noise near its detection threshold in participants with relatively low-balance ability. These findings suggest that an auditory noise improves static balance control via cross-modal SR.

Declarations

Author contribution statement

Junichiro Yashima: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Miki Kusuno: Conceived and designed the experiments; Analyzed and interpreted the data.

Eri Sugimoto: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data.

Hitoshi Sasaki: Conceived and designed the experiments; Wrote the paper.

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Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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