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Author(s)	Hasegawa, Naoya; Takeda, Kenta; Sakuma, Moe; Mani, Hiroki; Maejima, Hiroshi; Asaka, Tadayoshi
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Corresponding Author: Professor Tadayoshi Asaka, Ph.D.

Corresponding Author's Institution: Hokkaido University

First Author: Naoya Hasegawa, M.S.

Order of Authors: Naoya Hasegawa, M.S.; Kenta Takeda, M.S.; Moe Sakuma, M.S.; Hiroki Mani, Ph.D.; Hiroshi Maejima, Ph.D.; Tadayoshi Asaka, Ph.D.

Abstract: Augmented sensory biofeedback (BF) for postural control is widely used to improve postural stability. However, the effective sensory information in BF systems of motor learning for postural control is still unknown. The purpose of this study was to investigate the learning effects of visual versus auditory BF training in dynamic postural control. Eighteen healthy young adults were randomly divided into two groups (visual BF and auditory BF). In test sessions, participants were asked to bring the real-time center of pressure (COP) in line with a hidden target by body sway in the sagittal plane. The target moved in seven cycles of sine curves at 0.23 Hz in the vertical direction on a monitor. In training sessions, the visual and auditory BF groups were required to change the magnitude of a visual circle and a sound, respectively, according to the distance between the COP and target in order to reach the target. The perceptual magnitudes of visual and auditory BF were equalized according to Stevens' power law. At the retention test, the auditory but not visual BF group demonstrated decreased postural performance errors in both the spatial and temporal parameters under the no-feedback condition. These findings suggest that visual BF increases the dependence on visual information to control postural performance, while auditory BF may enhance the integration of the proprioceptive sensory system, which contributes to motor learning without BF. These results suggest that auditory BF training improves motor learning of dynamic postural control.

***2. Conflict of Interest Statement**

Learning effects of dynamic postural control by auditory biofeedback versus visual biofeedback training

Naoya Hasegawa[a, b], Kenta Takeda[a], Moe Sakuma[a], Hiroki Mani[c], Hiroshi Maejima[c], Tadayoshi Asaka[c*]

[a.] *Graduate School of Health Sciences, Hokkaido University, N12-W5, Kita-ku, Sapporo, Hokkaido 060-0812, Japan*
[b.] *Sapporo Yamanoue Hospital, Yamanote 6-9. Nishi-ku, Sapporo, Hokkaido 063-0006, Japan*
[c.] *Department of Rehabilitation Science, Faculty of Health Sciences, Hokkaido University, N12-W5, Kita-ku, Sapporo, Hokkaido 060-0812, Japan*

[*] Corresponding author
Tel/Fax: +81 11 706-3381; Email address: ask-chu@hs.hokudai.ac.jp

Abstract

Augmented sensory biofeedback (BF) for postural control is widely used to improve postural stability. However, the effective sensory information in BF systems of motor learning for postural control is still unknown. The purpose of this study was to investigate the learning effects of visual versus auditory BF training in dynamic postural control. Eighteen healthy young adults were randomly divided into two groups (visual BF and auditory BF). In test sessions, participants were asked to bring the real-time center of pressure (COP) in line with a hidden target by body sway in the sagittal plane. The target moved in seven cycles of sine curves at 0.23 Hz in the vertical direction on a monitor. In training sessions, the visual and auditory BF groups were required to change the magnitude of a visual circle and a sound, respectively, according to the distance between the COP and target in order to reach the target. The perceptual magnitudes of visual and auditory BF were equalized according to Stevens' power law. At the retention test, the auditory but not visual BF group demonstrated decreased postural performance errors in both the spatial and temporal parameters under the no-feedback condition. These findings suggest that visual BF increases the dependence on visual information to control postural performance, while auditory BF may enhance the integration of the proprioceptive sensory system, which contributes to motor learning without BF. These results suggest that auditory BF training improves motor learning of dynamic postural control.

Keywords: Auditory biofeedback; Body sway; Center of pressure; Postural control; Visual biofeedback

1. Introduction

Augmented sensory biofeedback (BF) for postural control is widely used to improve postural stability. Effects of BF have been reported in stroke [1], bilateral or unilateral vestibular loss [2], Parkinson’s disease [3], blindness [4], the elderly [5, 6], and young adults [7, 8]. Various forms of sensory information including visual [5, 8] and auditory [7, 9] have been used to provide real-time BF in the field of rehabilitation.

Most previous studies of postural control using sensory BF have used visual BF during quiet stance [6]. Typically, visual BF increased performance during acquisition, but not during retention tests [10, 11]. Bonan et al. [12] showed that balance training in stroke patients was more effective with visual deprivation than with free vision. These researchers suggested that visual overuse may be a compensatory strategy for coping with initial imbalance. On the other hand, several studies of postural control using auditory BF systems have been reported recently [3, 7]. Mirelman et al. [3] reported that auditory BF training for patients with Parkinson`s disease increased their performances, and these effects were sustained up to 4 weeks after the completion of the training.

Few studies have compared learning effects across visual and auditory BF systems. Ronsse et al. [13] compared the learning effects of consecutive visual and discrete auditory BF for flexion-extension movements with both wrists. They observed learning effects of discrete auditory BF but not consecutive visual BF under the no-feedback condition, despite similar adaptation effects of training between under the auditory and visual BF conditions. Using functional magnetic resonance imaging, the researchers demonstrated that brain activation increased in visual areas during practice sessions with visual BF. On the other hand, brain activation decreased in auditory areas and increased in a broad network response related with auditory and proprioceptive areas during practice sessions with auditory BF. By contrast, Chiou et al. [14] compared the learning effects of consecutive visual, discrete visual, and discrete auditory BF for bimanual movements and observed similar learning effects between discrete visual and discrete auditory BF but not consecutive visual BF under the no-feedback condition. However, the perceptual magnitudes of visual and auditory BF were not considered in these two studies. Moreover, the learning effects of postural control using visual versus auditory BF are not known.

This study aimed to assess the learning effects of visual and auditory BF during standing with voluntary body sway, in reference to the study of Radhakrishnan et al. [15]. The perceptual magnitudes of visual and auditory BF were equalized according to Stevens' power law [16] to compare the effects of visual and auditory BF training. Since previous studies suggested that visual BF induced a potential dependence of visual information that may prevent motor learning without visual BF [10, 11, 13], the hypothesis of this study was that the learning effects of postural control using auditory BF but not visual BF would be sustained under the no-feedback condition. The results of this study provide fundamental evidence for effective sensory BF training in dynamic postural control.

2. Methods

2.1. Participants

Eighteen healthy young adults with no known neurological disorders, motor disorders, or visual disability participated in this study. The participants were randomly divided into two groups. One group received augmented auditory BF; the other received augmented visual BF. Participants' age, sex, height, body weight, and foot length were recorded (Table 1). All the study protocols were approved by the ethics committee of the institution where the study was conducted, and written informed consent was obtained from all participants according to the Declaration of Helsinki.

2.2. Equipment

A force plate (Kistler, Winterthur, Switzerland) was used to calculate the COP coordinates in the anteroposterior (AP) direction. Force plate signals were collected at a sampling frequency of 1000 Hz and filtered with a fourth-order 10-Hz low-pass zero-lag Butterworth filter. Augmented real-time BF was presented on a 19-inch monitor or by two speakers located approximately 1 m from the participant using LabVIEW software (National Instruments, USA).

2.3. Procedures

Participants were instructed to stand barefoot with their arms across their chest with their feet parallel and positioned 1 cm medial to the right and left anterior superior iliac spine [17]. First, to measure the limitations of stability in the AP direction, participants were instructed to maintain maximum COP displacement for 30 s in each direction using a visual point indicating COP displacement. Only the AP direction was considered in order to reduce the feedback complexity and allow participants to focus on COP fluctuations along a single axis [18]. The point moved upward on the monitor, located at eye level, as the COP moved forward and vice versa. Foot position was standardized: 40% of the foot length from the heel was aligned with the center of the force plate in the sagittal plane [19]. The precise location for foot placement was marked on the force plate to ensure that all participants started each trial with the same foot position.

In the test sessions, participants were asked to bring real-time COP displacements in line with a hidden target by body sway. The target moved in seven cycles of sine curves at 0.23 Hz [15] in the vertical direction on the monitor as the COP moved for 35 s each trial. The target became visible on the monitor in synchronization with a beeping sound only when the target reached the sine-wave inflection points. The target fixed for 5 s, and then moved to 80% or 70% of the maximum COP displacement in the forward or backward direction of each participant, respectively. The participant performed four test sessions: pre-training, mid-training, and post-training on the same day, and then on the third day after training (hereafter called pre-test, mid-test, post-test, and retention, respectively) (Fig. 1).

In the training sessions, the visual BF group was required to bring the diameter of a yellow filled circle in line with a fixed blue open circle (15 cm diameter). The diameter of the yellow circle changed according to the distance between the real-time COP displacement and the moving target, growing to exceed that of the blue circle as the COP displacement shifted from the target in the forward direction (Fig. 2A, C) and shrinking as COP displacement shifted under from the target in the backward direction (Fig. 2B, C). The auditory BF group changed the volume of a sound, reducing it as the distance between the COP displacement and the target decreased. In addition, the generated sound was higher-pitched (3000 Hz) as COP displacement shifted from the target in the forward direction (Fig. 2C, D) and lower-pitched (1000 Hz) as COP displacement shifted from the target in the backward direction (Fig. 2C, E). The perceptual magnitudes of visual BF and auditory BF were equalized according to Stevens’ power law [16] as follows:

$$S = D^{1/n} \qquad (1)$$

where *S* is the perceptual magnitude, *D* is the distance between the COP displacement and the target, and n is defined by the sensory modality (visual: 0.9, auditory: 0.3). The participants of both groups performed the two training sessions (2 × 4 blocks) with a 5-min rest between the blocks. In the test and training sessions, one block consisted of 5 trials, and each trial had a duration of 35 s. The total time per training session was 11 min and 40 s (4 blocks × 5 trials × 35 s). Participants in each group were allowed to familiarize themselves with the task for 30 s.

2.4. Data and Statistical Analysis

All signals were processed offline using MATLAB software (MathWorks, Natick, MA, USA). The force plate data were filtered with a fourth-order 8-Hz low-pass zero-lag Butterworth filter. Although the signals obtained in the test session had seven cycles, only six cycles were analyzed, excluding the first sine curve to clear the timing error during the initiation of body sway. To evaluate the effects of motor learning, the average and standard deviation (SD) of the distance between COP displacement and the target were calculated for the six cycles in each trial. Then, the average (D_{ave}) and SD (D_{SD}) across five trials in each block were calculated.

To evaluate the learning effects including temporal domain, the coherence spectrum was calculated, which represented the degree of correlation between COP displacements and the target points in the frequency domain [20]. Coherence is a function of the power spectral density of the COP displacement and the target signal and the cross-power spectral density of the two signals. Magnitude-squared coherence is estimated as a function of sway frequency, with coherence values indicating the correspondence of the COP displacement signal to the target signal at each frequency bin ranging from 0, absence of any temporal relationship between the signals, to 1, perfect synchrony. The function determined the magnitude-squared coherence estimate of the two signals using Welch's method with 6 segments of non-overlapping Hanning windows (frequency resolution = 0.01Hz) to average modified periodograms. The peak coherence at 0.23 Hz was estimated on a subject-by-subject basis. The 95% confidence limit for the coherence spectrum was 0.45. The significant value was determined from the total segments per subject as follows:

$$1 - (0.05)^{1/(L-1)} \qquad (2)$$

where L is number of the total segments [21].

Two-way mixed-design ANOVA was used with the factors *Group* (visual BF and auditory BF) and *Test session* (pre-, mid-, post-test, and retention) to analyze possible differences in the values of these indices. Post-hoc analysis was performed using Bonferroni pairwise comparison. To investigate the relationship between learning effects in spatial and temporal domains, Pearson's correlation coefficient was used to analyze possible correlations between the relative values of D_{SD} and the relative values of coherence in the auditory BF group. The relative values were calculated as the values of coherence and D_{SD} on the retention test divided by those on the pre-test. Statistical significance was set at $p < 0.05$.

3. Results

No significant differences were found between the two groups in terms of participants' age (t_{16} = 0.855, p = 0.405), height (t_{16} = -0.828, p = 0.420), weight (t_{16} = -0.833, p = 0.417), or foot length (t_{16} = -0.699, p = 0.495) (Table 1).

Figure 3 shows examples of single trial trajectories for the COP movement made to the target on the pre-test and retention test of the auditory BF group (Fig. 3A and B) and the visual BF group (Fig. 3C and D). Note that the rapid small COP movements during change in the AP direction were apparent on the pre-test in both groups (Fig. 3A and 3C). By contrast, the rapid small movements decreased on the retention test compared with the pre-test in the auditory BF group (Fig. 3B) but remained similar to those on the pre-test in the visual BF group (Fig. 3D).

No significant main effect was found for the factor *Group* in terms of D_{ave} ($F_{1,\,17} = 0.579$, $p = 0.458$) or in terms of D_{SD} ($F_{1,\,17} = 3.836$, $p = 0.068$). A significant main effect was found for the factor *Test session* in terms of D_{ave} ($F_{3,\,17} = 5.515$, $p = 0.002$) and in terms of D_{SD} ($F_{3,\,17} = 9.757$, $p < 0.001$). No significant interaction was found between the two factors in terms of D_{ave} ($F_{3,\,17} = 1.344$, $p = 0.271$; Fig. 4A), but a significant interaction was found between the two factors in terms of D_{SD} ($F_{3,\,17} = 3.154$, $p = 0.033$). Post-hoc testing revealed that D_{SD} was significantly lower in the auditory BF group than in the visual BF group in the mid-test ($p = 0.019$) and retention test ($p = 0.009$; Fig. 4B). For the auditory BF group, D_{SD} in the mid-test, post-test, and retention test was significantly lower than that in the pre-test ($p < 0.001$); however, in the visual BF group, the pre-test did not significantly differ from the other test sessions ($p > 0.05$).

The coherence spectrum of the magnitude of coherence showed no significant main effect for the factor *Test session* ($F_{3,\,17} = 0.673$, $p = 0.573$), a significant main effect for the factor *Group* ($F_{1,\,17} = 7.064$, $p = 0.017$), and a significant interaction between the two factors ($F_{3,\,17} = 3.258$, $p = 0.029$). Post-hoc testing revealed that the magnitude of coherence was significantly higher in the auditory BF group than in the visual BF group in the post-test ($p = 0.022$) and retention test ($p = 0.027$; Fig. 5A). In the auditory BF group, the magnitude of coherence in the mid-test, post-test, and retention test was significantly higher than that in the pre-test ($p < 0.01$). In the visual BF group, the pre-test did not significantly differ from the other test sessions ($p >$

0.05). The relative values of D_{SD} and coherence were significantly negatively correlated in the auditory BF group ($r = -0.70$, $p = 0.035$; Fig. 5B).

Discussion

The main finding of this study is that auditory BF training but not visual BF training improved the variability of distances (Fig. 4B) and the coherence (Fig. 5A) between COP displacements and the target under the no-feedback condition on the retention test compared with those on the pre-test. These results suggest that auditory BF training contributes to motor learning, that is, variabilities of postural performance in spatial and temporal domains, but visual BF training does not.

Several studies demonstrated that visual BF was able to enhance performance in the acquisition phase, but that these performance gains were lost or reduced without BF. Radhakrishnan et al. [22] found that postural responses to Achilles tendon vibration were augmented more by auditory-guided anteroposterior body sway than by visually guided anteroposterior body sway. These researchers suggested that sensory reweighting processes may have decreased the proprioceptive contribution to control of the sway task and increased reliance on visual input in visually guided sway. This phenomenon is known as “visual dominance,” or the tendency for visual input to hold priority in perception or memory processing and resources [23]. Taken together with the report by Ronsse et al. [13] described in the Introduction, these findings suggest that visual BF increases dependence on visual information to guide behavior, while auditory BF may create a more challenging learning environment that encourages gradually increased reliance on proprioceptive information. Therefore, auditory BF training may enhance the integration of proprioceptive sensory systems that contribute to motor learning without the BF.

The two factors (*Group* × *Test session*) demonstrated no significant interaction in terms of D_{ave} (Fig. 3A) but a significant interaction in terms of D_{SD} (Fig. 3B). In general, motor learning reflects the gradual reduction in variability of postural performance in the newly developed motor program via sensory feedback such as the visual, vestibular sensory and somatosensory systems [24]. In this study, the rapid small COP movements during change in the AP direction were similar in the retention test and pre-test in the visual BF group (Fig. 3D). By contrast, the small COP movements on the retention test during change in the AP direction decreased compared with those on the pre-test in the auditory BF group (Fig. 3B). Therefore, motor learning gains could be more readily detected by the standard deviation of performance (D_{SD}) than by the accuracy of performance (D_{ave}).

Furthermore, the observed relationship between learning effects in the spatial and temporal domains indicated that smaller relative values of D_{SD} correlated with larger relative values of coherence (Fig. 5B). Thus, this result suggests that the decrease in spatial errors was associated with the decrease in temporal errors. The time period of consecutive small COP movements during change in the AP direction may induce not only spatial error but also temporal error. The rapid small movements around the target points may be derived by feedback-based corrections to achieve the target [25]. Learners can develop an internal movement representation or motor program through a repetitive feedback-based correction process, which then assists them to execute a movement independently [14]. Therefore, the increased dependence on visual information by visual BF may prevent a gradual shift from feedback control to predict internal feedforward control for motor learning [26].

As limitations of this study, this experiment was performed with a small number of participants. In addition, the rhythmic movements of the task in this study may influence motor learning of auditory BF earlier than that of visual BF [14]. Furthermore, not only the parameters of performance, reflecting controlled results, but also parameters such as coordination across postural muscle synergies determined by electromyography should be quantified in future studies [27].

The task in this study demonstrated that consecutive auditory BF affected motor learning via voluntary body sway in dynamic postural control, similar to the study of Ronsse et al. [13] in voluntary movements. By contrast, static postural control is strongly influenced by automatic responses, which are considered to reflect a feedback mechanism [28] and feedforward mechanism [29]. Overall, visual BF of the COP did not improve postural stability during quiet standing, consistent with previous research [30]. Whether the findings of this study are also applicable to static postural control should be addressed in future studies.

4. Conclusion

This study indicated differences in the learning effects of augmented visual and auditory BF training during standing with voluntary body sway. Auditory BF training improved the variability of postural performance in spatial and temporal domains compared with visual BF training. The results of this study suggest that auditory BF training, but not visual BF training, improves motor learning of dynamic postural control. These results provide fundamental evidence for effective sensory BF training in dynamic postural control. The findings provide theoretical perspectives on the use of augmented BF, as well as clues to prevent potential dependence of visual BF such as a mirror or monitor reflecting practical performance in the field of sports as well as rehabilitation.

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Conflict of interest statement

The authors declare that there is no conflict of interest.

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Figure Captions

Figure 1. Experimental protocol

White boxes indicate four test sessions, and black boxes indicate two training sessions. The participants performed four test sessions: pre-test, mid-test, and post-test on one day (Day 1) and retention on the third day after training (Day 3) without sensory biofeedback. The training sessions consisted of 8 blocks (2 × 4 blocks) with sensory biofeedback. One block consisted of 5 trials, and each trial (seven cycles) had a duration of 35 s.

Figure 2. Visual and auditory biofeedback (BF) stimulation

For visual BF, the diameter of the yellow circle changed according to the distance between the real-time center of pressure (COP) displacement and the moving target in the AP direction. The area grew beyond that of the blue circle as COP displacement shifted from the target in the forward direction (A) and shrank as COP displacement shifted from the target in the backward direction (B). Six cycles were analyzed, excluding the first sine curve (C). For auditory BF, the volume changed according to the distance. The sound generated was higher-pitched (3000 Hz) as COP displacement shifted from the target in the forward direction (D) and lower-pitched (1000 Hz) as

COP displacement shifted from the target in the backward direction (E).

Figure 3. Examples of single trial trajectories for center of pressure (COP) movement

Solid lines represent COP movement and dotted lines represent target movement. COP movements are shown on the pre-test (A) and retention test (B) of the auditory biofeedback (BF) group, and on the pre-test (C) and retention test (D) of the visual BF group. The rapid small COP movements during change in the AP direction on the retention test decreased in the auditory BF group compared with those in the visual BF group.

Figure 4. Average (A) and standard deviation (SD) (B) of the distances between the center of pressure (COP) displacement and the target

The black circles represent the auditory biofeedback (BF) group, and the white squares represent the visual BF group. The SD of the distances (D_{SD}) was significantly lower in the auditory BF group than in the visual BF group at the mid-test and retention ($*p < 0.05$). For the auditory BF group, D_{SD} was significantly lower at the mid-test, post-test, and retention than at the pre-test ($*p < 0.05$). N.S.: non-significant

Figure 5. Magnitude of coherence between the center of pressure (COP) displacement and the target (A), and relationship between the relative values of D_{SD} and the relative values of coherence (B)

(A) Black circles represent the auditory biofeedback (BF) group, and white squares represent the visual BF group. The magnitude of coherence was significantly higher in the auditory BF group than in the visual BF group at the post-test and retention ($*p < 0.05$). For the auditory BF group, the magnitude of coherence was significantly higher at the mid-test, post-test, and retention than at the pre-test ($*p < 0.05$). (B) The relative values were calculated as the values of coherence and D_{SD} on the retention test divided by those on the pre-test. The relative values of D_{SD} and coherence were significantly negatively correlated in the auditory BF group ($r = -0.70$, $p = 0.035$; Fig. 5B). N.S.: non-significant

6. Table(s)

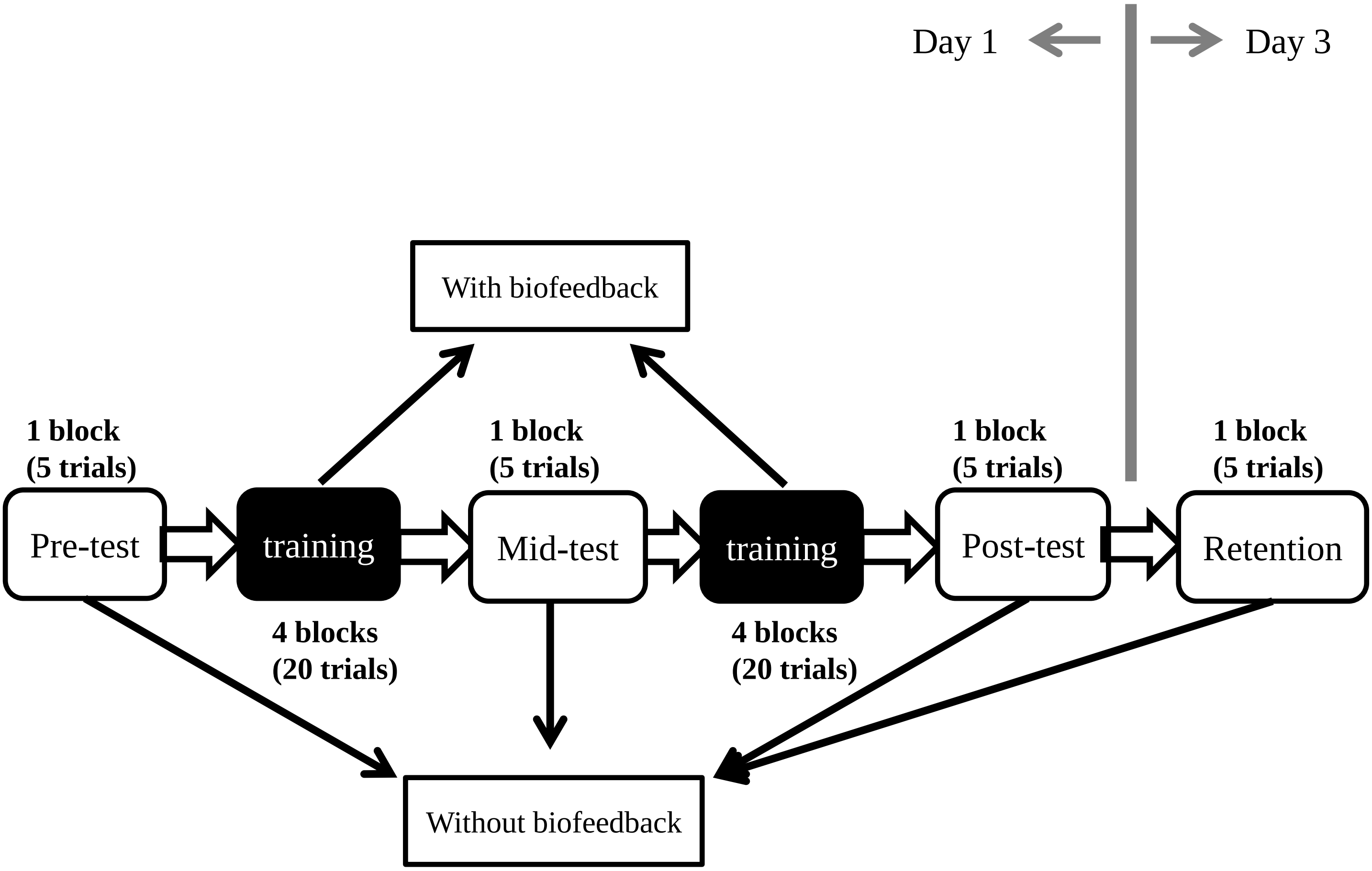
Table 1
The characteristics of the auditory FB and visual FB groups

	auditory FB (n = 9)	visual FB (n = 9)
Age (years)	23.2 ± 2.1	22.6 ± 0.5
Sex	4 male, 5 female	4 male, 5 female
Height (cm)	162.9 ± 6.9	166.5± 10.3
Weight (kg)	54.7 ± 6.7	58.6 ± 11.3
Foot length (cm)	23.7 ± 1.0	24.3 ± 2.3

Mean ± SD

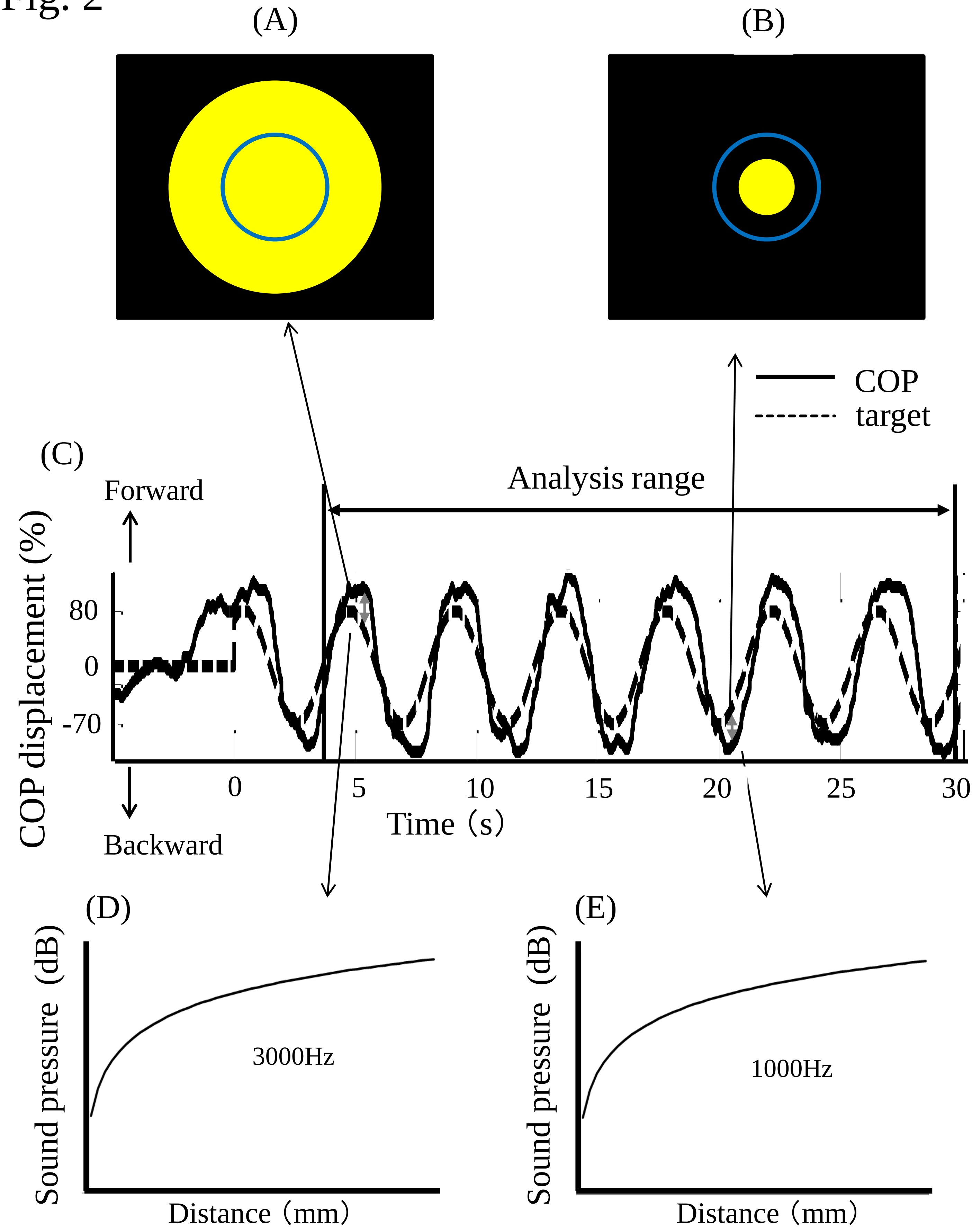
7. Figure1

Fig. 1



7. Figure2

Fig. 2



7. Figure3

Fig. 3

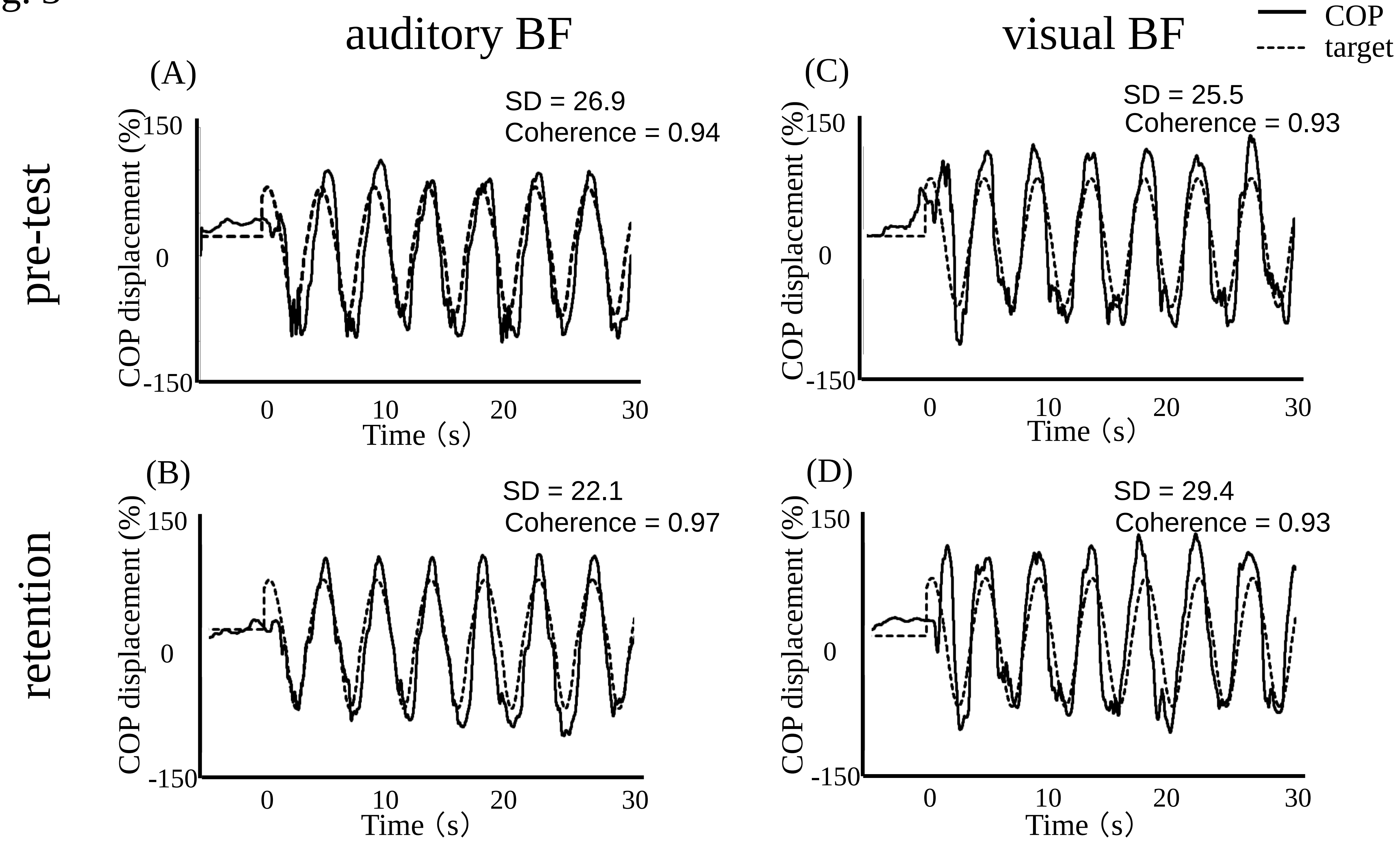
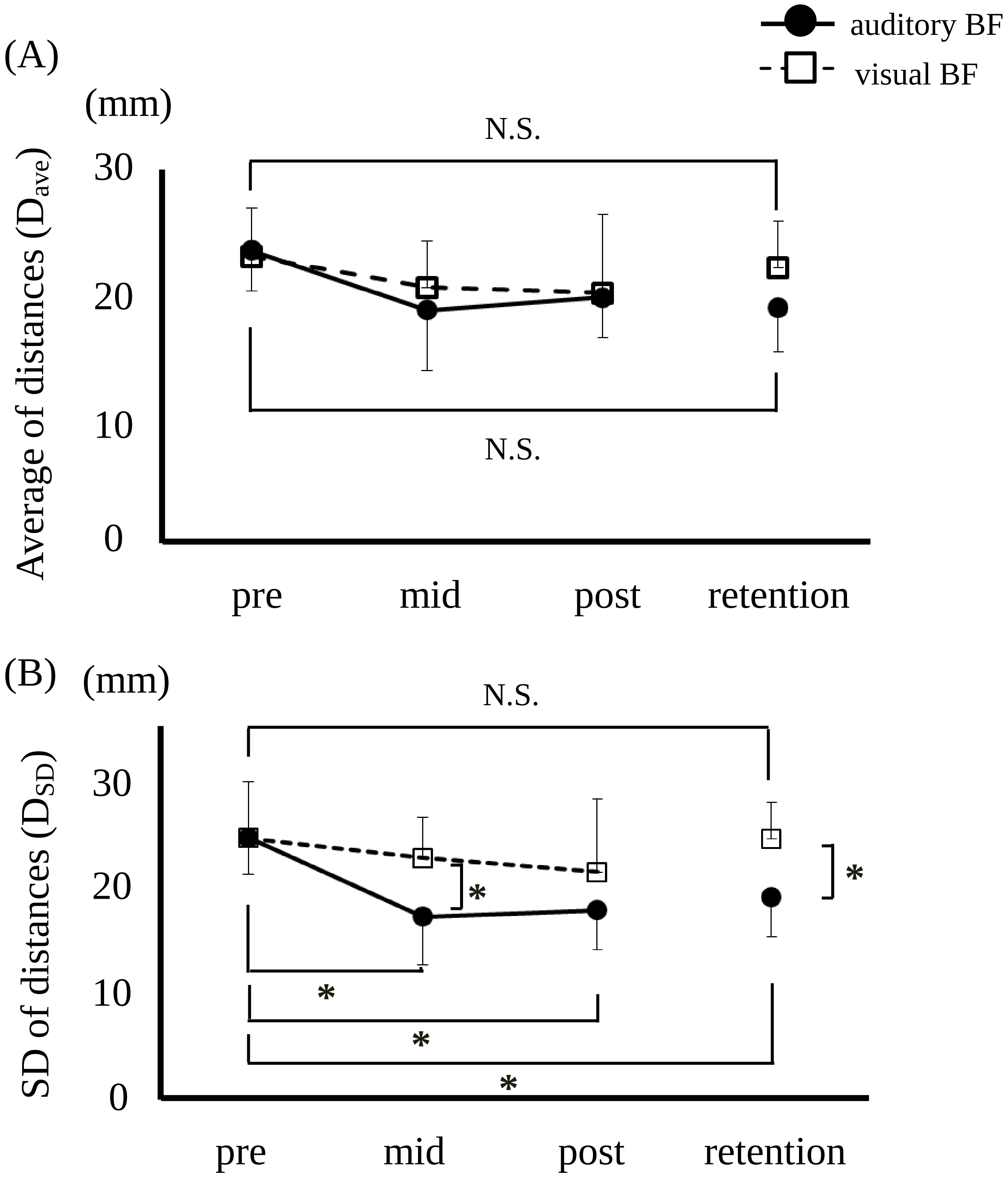
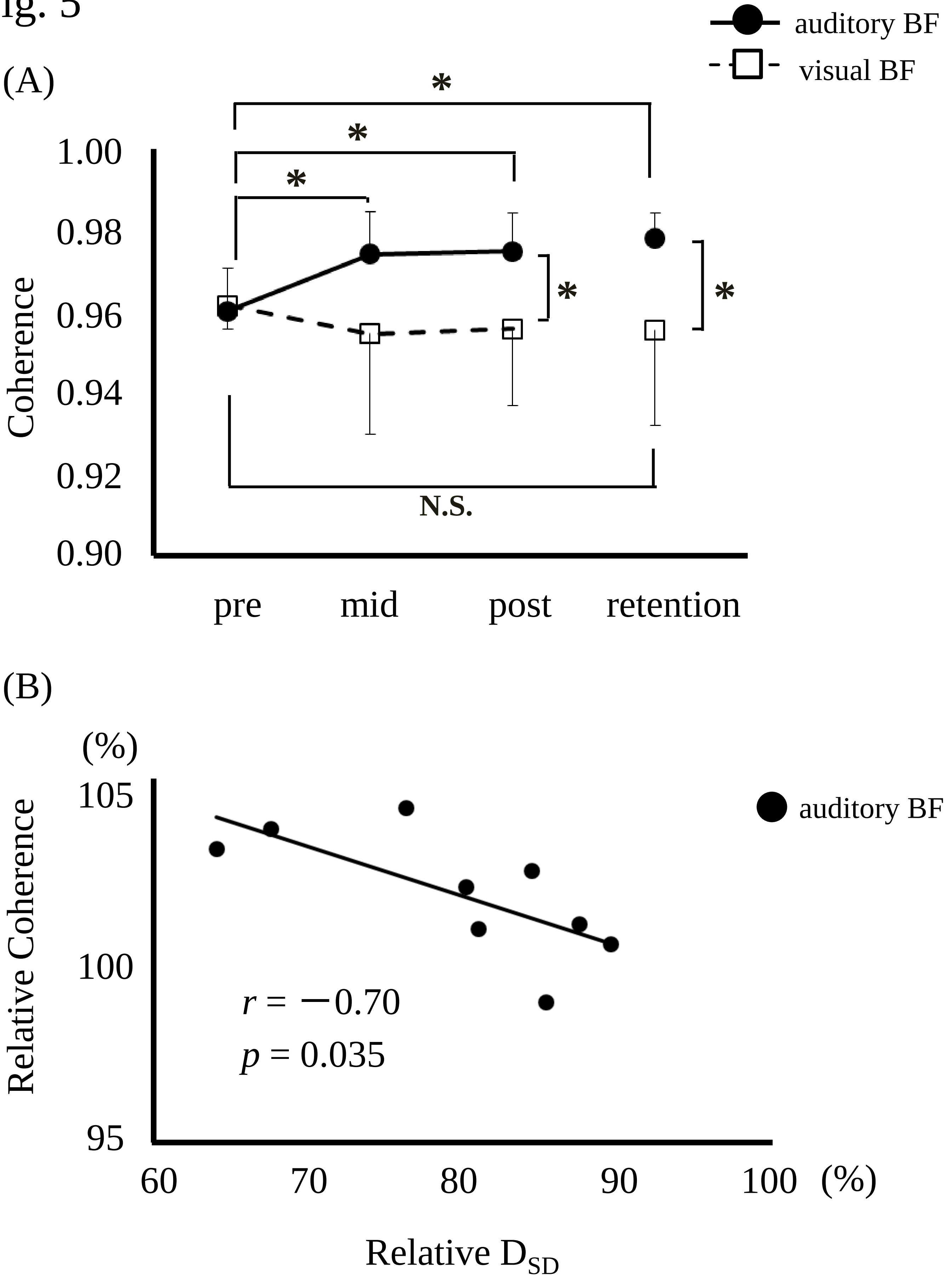


Fig. 4



auditory BF
visual BF
(A)
(mm)
Average of distances (D_{ave})
30
20
10
0
N.S.
N.S.
pre
mid
post
retention
(B)
(mm)
SD of distances (D_{SD})
30
20
10
0
N.S.
*
*
*
*
*
*
pre
mid
post
retention

Fig. 5


auditory BF
visual BF
(A)
*
*
*
*
*
1.00
0.98
0.96
0.94
0.92
0.90
Coherence
N.S.
pre
mid
post
retention
(B)
(%)
105
100
95
Relative Coherence
auditory BF
r = −0.70
p = 0.035
60
70
80
90
100
(%)
Relative D_SD

8. Supplementary Material

***Research Highligts**

- Learning effects of auditory BF versus visual BF training were investigated.
- Sensory BF changed according to the distance between the real-time COP and target.
- Auditory BF but not visual BF decreased spatial and temporal variability.
- Auditory BF training may improve motor learning of dynamic postural control.