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

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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.

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

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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.

Table 1
The characteristics of the auditory BF and visual BF groups.

	auditory BF (n = 9)	visual BF (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.

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:

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

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