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ACOUSTIC CUES AND POSTURAL CONTROL

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ABSTRACT. The effect of auditory input on postural control was evaluated in separate experiments performed in three groups of healthy volunteers. Auditory input took the form either of feedback signals generated by a force platform in response to the subject's postural control movements, or of field orientation (frame of reference) input provided by repeated clicks emitted by loudspeakers in a normally reverberative environment. The effect of these acoustic cues was measured in terms of body sway recorded on a force platform during stance perturbations induced by vibratory stimuli applied to the calf muscles either at low (120 mW) or high (850 mW) intensity, the subject standing with eyes closed or open, as instructed. In the presence of feedback auditory input, body sway in response to low intensity vibratory stimulation was significantly reduced, but not that in response to high intensity stimulation. This may be due to the fact that the head and body movements induced by high intensity vibratory stimulation are so rapid and powerful that they override the information available or to the subject using other strategies for postural control in which auditory feedback, at least in the form used here, does not contribute useful information. The availability of field orientation input did not reduce body sway in response to vibratory stimulation at low intensity. This was probably due to the cognitive lag which precluded use being made of the input before the fast proprioceptive responses to vibratory stimulation had already occurred.

Key words: vestibular, audio, posture, vibration, human.

INTRODUCTION

The ability of humans to stand upright, stabilise the body and simultaneously perform motor tasks is based upon complex feedback and feedforward mechanisms of the central nervous system (CNS) in response to afferent visual, vestibular and proprioceptive information as well as information from the pressure receptors of the soles of the feet (22). Together with hearing (14), this afferent sensory information provides a basis for orientation in space.

Several animal species are capable of using auditory information, both in feedback and feedforward loops, for orientation purposes and to facilitate the performance of motor tasks essential for survival (18). Humans with normal hearing can locate sound sources with good precision, which is the basis for the use of diverse sounds in daily life as warning signals or to facilitate orientation in space (14, 17). Moreover, humans exposed to rotating sound fields, where visual information has been eliminated, experience an illusion of self-rotation, and may even manifest nystagmus (11). Biofeedback using auditory input to augment motor performance has also been used in physiotherapy to facilitate weight bearing on one leg in amputees (21), as well as in flight simulators to enhance instrumental flight skills (12).

Whether humans can use auditory input as an exteroceptive source of information only, or whether information useful to postural control can be obtained from auditory feedback input is not known. The aim of this study was to ascertain whether humans could use auditory input in a feedforward or feedback manner to enhance motor control of posture during quiet or perturbed stance.

MATERIAL AND METHOD

Three different experiments were performed on healthy paid volunteers with normal pure tone audiograms and no history of otological or CNS disease or head trauma. The subjects were naive inasmuch as they were not previously informed about the test routine and they were not allowed to become aquainted with the equipments or practice. The subjects abstained from any drugs or alcohol during the 24-hour period preceding the tests (Table I).

Two types of auditory input were used: feedback sound signals deriving from body movements, and sound from

Table I. *Number and age of subjects in each experiment*

Experiment	Number Female	Male	Age
I	12	12	Range 20–44 Mean 28
II	17	7	Range 20–44 Mean 36
III	6	6	Range 21–41 Mean 30

loudspeakers providing a frame of reference. The stabilising effect of such auditory input on perturbed body posture was investigated. Body sway was recorded with a force platform, the changes in the centre point of force (CPF) actuated by the feet on the platform being digitized and sampled at 10 Hz by computer (COMPAQ 486/25). The subjects were instructed to stand erect but relaxed on the force platform with heels together, feet at an angle of thirty degrees, and arms crossed over the chest.

The feedback auditory input was provided by sound signals generated by body movements acting up on a force platform connected to a voltage-controlled signal generator (Wavetec, model 164), and consisting of a sinusoidal tone the frequency of which changed in response to the movement of the body in the sagittal plane—i.e., increasing in pitch when the subject leaned forward and decreasing in pitch when the subject leaned backward. The feedback signal was relayed to the subject through earphones (Figs. 1 and 4).

The field orientation (frame of reference) auditory input consisted of series of clicks emitted by two loudspeakers placed at head height to the front and right of the subject (Fig. 2). The clicks, produced by a 0.125 msec rectangular electrical pulses repeated at a frequency of 8.5 Hz, emerged from one or the other of the two loudspeakers randomly selected by a PRBS (pseudo-random binary stimulus) schedule run during the experiment.

Before the present set-up was chosen, several alternatives were tried, using pure sinus tones or clicks at different

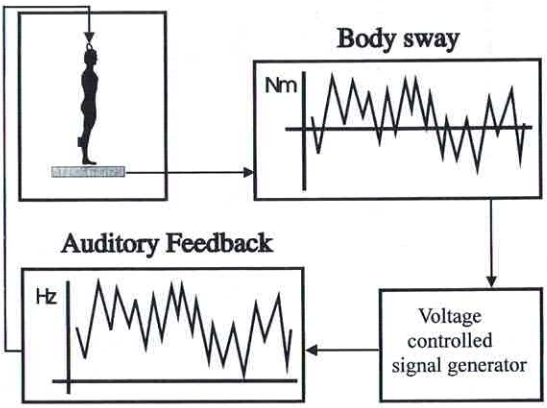

Fig. 1. Diagram of feedback sound signal generation from body sway.

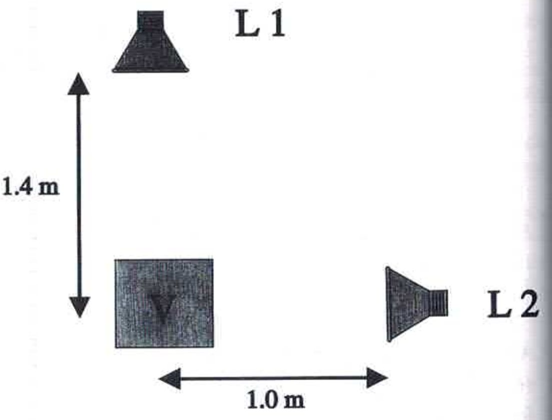

Fig. 2. Field orientation (frame of reference) set-up. L1 and L2 are loudspeakers, and V the force platform.

frequencies, both in anechoic and in reverberative chambers. The present set-up was chosen as providing a three-dimensional frame of reference (i.e., field orientation), while avoiding the possibility of harmonics from the two sound sources, confusing the subject.

The intensity of the auditory input was 85 db SPL (sound pressure level) when measured at ear level, for both feedback and frame of reference signals (Brüel and Kjaer, Sound Level Meter, 2218).

In control tests when subjects were provided with neither auditory feedback or feedforward input, they were provided with earphones relaying music (the Haffner serenade by Mozart) to mask possible orientational clues from environmental noise. All tests were performed in a normally reverberative chamber.

Vibratory stimulation applied through vibrators attached with elastic straps on the belly of the right and left gastrocnemius muscles were used to elicit perturbation of posture by disturbing proprioception—i.e., vibration-induced body sway (6, 7). For detailed description of this vibratory system, see Eklund (5). In experiments using feedback auditory input, both high intensity (850 mW, amplitude 1.0 mm, frequency 60 Hz) and low intensity (120 mW, amplitude 0.4 mm, frequency 60 Hz) vibrators were used to elicit stronger or weaker perturbations, respectively. The power supply to the vibrator's DC-motor (Escap, Switzerland) was provided by a custom-built generator and the vibratory stimulus was switched on/off according to a PRBS schedule. The frequency and amplitude of the vibratory stimuli were checked unloaded and loaded (attached to calf muscles) as a part of routine laboratory procedure. Vibration was measured by an accelerometer (Brüel and Kjaer 4374), amplitude was then calibrated with a calibrations exciter (Brüel and Kjaer 4294), and finally analysed with a high resolution analysator (Brüel and Kjaer 2033).

All experiments consisted of three test sequences: A, eyes open; B, eyes closed; and C, eyes closed; and feedback or feedforward auditory input scheduled according to a Latin design (Table II).

Sway variance in the sagittal plane was calculated and evaluated with the 386-Mat lab software (Mathworks Inc, USA). As calculated values for sway variance within each experimental group tended to be skewed, they were log-transformed (natural log) for normal distribution to allow the use of parametric tests performed with statistical

Table II. *Test set-up regarding eye status, auditory input and vibratory stimuli*

Experiment	Test sequences: Time		Eye status	Sound	Vibration
I	204 sec PRBS stimulus preceded by 30 sec rest	A	Open	Music	60 Hz-freq.
		B	Closed	Music	0.4 mm-ampl.
		C	Closed	Feedback	120 mW-effect
					3.5 g Low
II	256 sec PRBS stimulus preceded by 30 sec rest	A	Open	Music	60 Hz-freq.
		B	Closed	Music	0.4 mm-ampl.
		C	Closed	Reference	120 mW-effect
					3.5 g Low
III	204 sec PRBS stimulus preceded by 30 sec rest	A	Open	Music	60 Hz-freq.
		B	Closed	Music	1.0 mm-ampl.
		C	Closed	Feedback	850 mW-effect
					7.0 g High

software (JMP 2.0; SAS Institute Inc. USA). The Shapiro-Wilk test was used to check the normal distribution of the log-transformed sway variance values. Three-way analysis of variance with a multivariate model (Fig. 3) was used to evaluate the difference between test sequences A, B and C in each experiment, p-values $\leqslant 0.05$ being considered statistically significant.

RESULTS

In all three experiments (I, II, III), variance of sagittal body sway increased significantly when visual clues were eliminated (i.e., the subject standing with eyes closed; test B), as compared to the eyes open condition (test A) without simultaneous auditory input (Figs. 4 and 5).

The availability of feedback auditory input (test C) significantly reduced the variance of body sway in subjects standing with eyes closed during perturbations at low intensity vibration (Experiment I), whereas the availability of an auditory frame of reference did not (experiment II). With stronger perturbation of posture, and hence more rapid movements (i.e., during stimulation with high intensity vibration, experiment III), the feedback auditory input did not succeed in reducing the body sway (Fig. 5).

DISCUSSION

Auditory feedback input deriving from the antero-posterior movement of the centre point of force actuated by the feet, reduced body sway in healthy subjects during perturbation of posture by vibration at low intensity (120 mW), but not during vibration at high intensity (850 mW) causing stronger perturbation. The availability of an auditory frame of reference

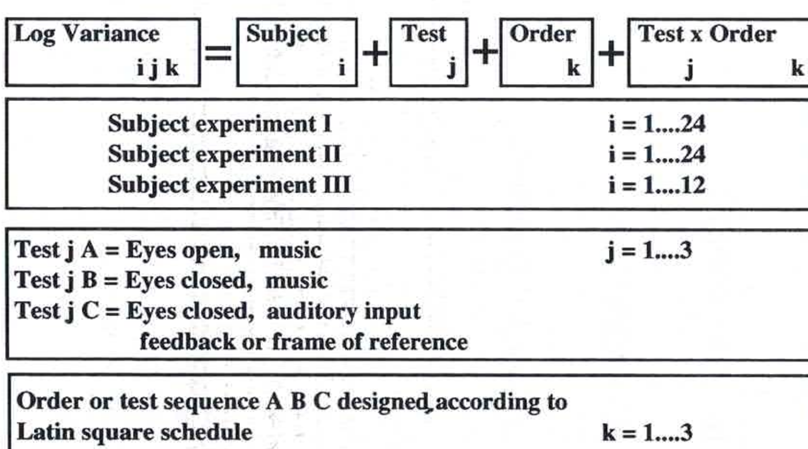

Fig. 3. Mathematical model for the three-way analysis of variance.

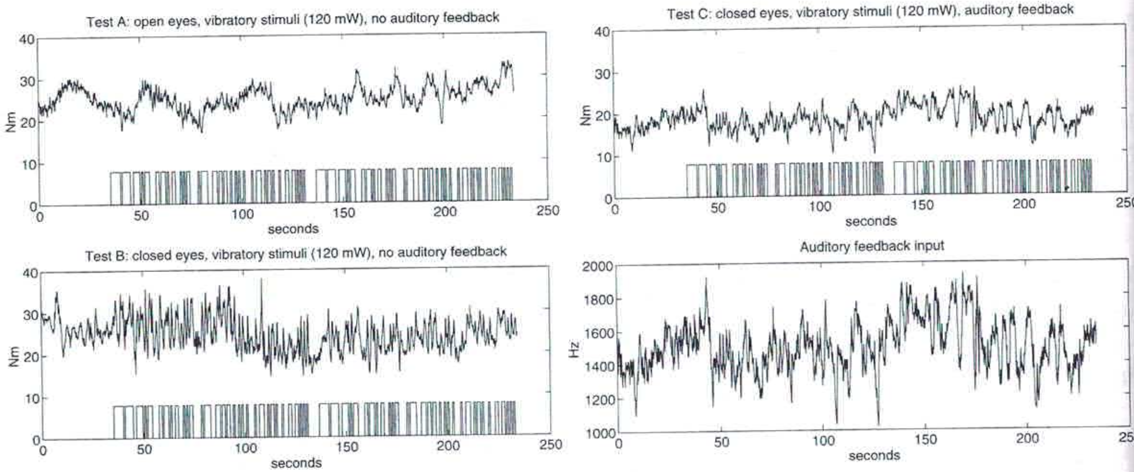

Fig. 4. Results for one subject during experiment I. The body sway in the antero-posterior plane is given for all three tests performed together with a graphic illustration of the auditory input. Note the same shape of the curves in test C and auditory feedback input, only different amplitude.

(i.e., field orientation) did not reduce the body sway, even though the postural perturbations were of low intensity. The availability of visual information (i.e., the eyes open test condition) reduced body sway significantly, as compared to the eyes closed test condition, irrespective of whether the intensity of vibratory stimulation was high or low, a finding consistent with those obtained previously (8).

Vibration to the calf muscles activates proprioceptive receptors and induces the body sway (6, 7, 8). Vibration-induced body sway has been found useful in several studies of postural control, and in standing subjects during hypothermally reduced pressure (somatosensory) input from the feet (13), as well as in studies of patients with peripheral or central vestibular lesions (16). Vibration of sufficient intensity can cause manifest disturbance of posture, and may induce falls even in normal subjects (7). In the present experiments, two different intensities of calf muscle vibration were used to elicit perturbations: low intensity vibration (120 mW), or high intensity vibration (850 mW) inducing faster and more pronounced body sway.

In the present study, the subjects were less than 45 years of age. This may have effect on the results. However, vibration induced body sway seems to be stable from 15 years to at least 75 years of age, and even a slight decrease of sway velocities may be observed in subjects between 75–90 years (9). The reduction of the low intensity vibration-induced body

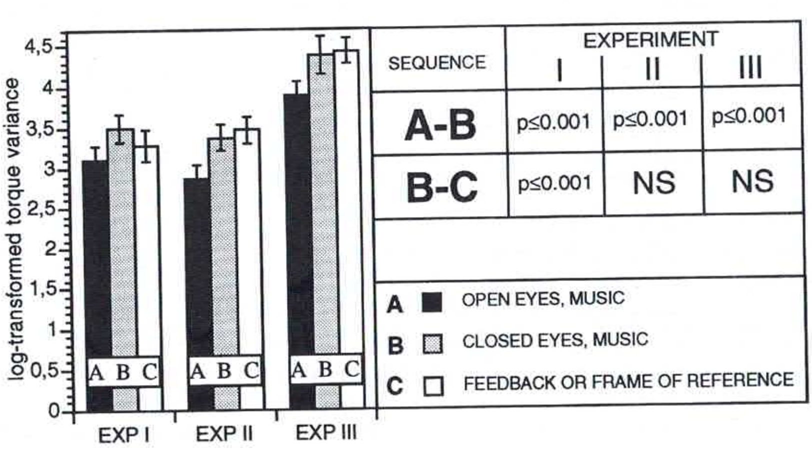

Fig. 5. Log-transformed torque variance. The mean, SEM and level of significance are given in each experiment.

sway during auditory feedback might thus be improved further in older subjects.

The low intensity vibration (120 mW) causes less manifest body movements, resulting in slower frequency changes of the auditory feedback input. The auditory feedback input reflects the changes in forces actuated by the feet during body movements, but does not directly reflect changes due to head movements. This may explain why feedback auditory input was more effective in reducing slower body perturbations, where the use of a so-called ankle strategy may be expected (10), and the audio reaction time of the feedback sound above 500 ms (2) is not a limiting factor. These slow vibration-induced body movements and the auditory feedback input generated from them may also interact to reduce body sway as the other receptor systems (vestibular and somatosensory) required for postural control are intact and contribute effectively to the stabilisation of posture. Experiments using an auditory input feedback system based on major excursions of body posture during quite stance based on major excursions of body posture during quiet stance have yielded similar results—i.e., have shown the effectiveness of feedback auditory input in reducing body excursions (19).

In experiment II, the field orientation or reference frame auditory input was not effective in reducing vibration-induced body sway, even though the perturbations were of low intensity. However, this does not rule out the possibility that the control of body posture might be facilitated by auditory input from a fixed external frame of reference, although this seems to be a less important input for postural control than vestibular and somatosensory input during proprioceptive perturbation of normal subjects. In animals, the topographic representation of auditory space in the central nervous system is well known (1, 15), and provides a basis for orientation and monitoring of body movements as well as movements of the environment when integrated with information from other receptor systems (i.e., the visual, vestibular and proprioceptive information required for postural control). Environmental sound providing an auditory frame of reference, field orientation input, is known to be effective in the spatial orientation of the blind, for instance (20), although in daily life the non-visually handicapped human uses visually determined frames of reference for spatial orientation, auditory input constituting a supplementary frame of reference requiring adequate training to become effective. In experiment II, untrained subjects, apparently unable to utilise the field orientation input (i.e., the sound shift between the two loudspeakers) in their efforts to maintain postural control, manifested increased body sway.

In experiment III, body posture was perturbed with high intensity vibration (850 mW) causing fast and prominent changes in the centre point of force, and hence in the feedback auditory input. Owing to cognitive lag (2), feedback auditory input can not be interpreted quickly enough to permit the fast and intensive changes in body posture to be compensated, and the potential stabilising effect of the feedback auditory input is thus negated. The fast and intensive changes in body posture caused by high intensity vibration (850 mW) may also require another postural strategy (10) which does not take into account the delicate and time-dependent effect of the feedback auditory input required to reduce body sway significantly. Fast angular movements at the ankle may also evoke activity in the antagonistic muscles so as to diminish the initial compensatory reaction to the test perturbations (3, 4) caused by high intensity vibration (850 mW) and thus further increase the frequency shift in the auditory feedback input.

The effect of auditory feedback stabilisation of vibration-induced body sway may be useful in rehabilitation contexts as well as in training programmes aimed at augmenting human skills. The present results suggest that auditory feedback may be better suited for training where position deviations are present (as in stroke patients) than to supplement recognition of and response to fast movements.

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