Sensory Supplementation through Tongue Electrotactile Stimulation to Preserve Head Stabilization in Space in the Absence of Vision

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PURPOSE. To investigate the effectiveness of a head position-based, tongue-placed biofeedback system in providing sensory supplementation to preserve head stability in space in the absence of visual information.

METHODS. Nine healthy young men with normal vision and no history of previous motor problems, neck injury, vertigo, neurologic disease, or vestibular impairment voluntarily participated in the experiment. They were asked to stand, their feet placed in a semitandem position, as immobile as possible in two conditions of No Vision and Vision and two conditions of No Biofeedback and Biofeedback. In the Biofeedback condition, subjects executed the postural task using a biofeedback system whose principle consisted of supplying them with additional information about their head orientation/motion with respect to gravitational vertical through electrotactile stimulation of the tongue. A system for the analysis of movement was used to record the head displacements.

RESULTS. Without the provision of the biofeedback (No Biofeedback condition), the No Vision condition yielded increased head displacements along the mediolateral axis compared with the Vision condition. Conversely, when biofeedback was available (Biofeedback condition), no significant difference between the No Vision and Vision conditions was observed.

CONCLUSIONS. These results suggest that healthy young subjects were able to efficiently use head position-based, tongue-placed biofeedback to suppress the head instability induced by the suppression of vision. Hence the present findings demonstrate the effectiveness of a head position-based, tongue-placed biofeedback in providing sensory supplementation to preserve head stability in space in conditions of absent visual information. (Invest Ophthalmol Vis Sci. 2009;50:476–481) DOI:10.1167/iovs.07-1595

Head stabilization in space is recognized as crucial for effective postural control and segment coordination during the execution of various motor and locomotor tasks. In fact, as an inertial guide platform, head stabilization is thought to improve the interpretation of vestibular inputs for balance, especially when visual and somatosensory inputs are absent, degraded, or incongruent.

A possible way to improve head stabilization in space is the use of a biofeedback system in a balance prosthesis. For instance, Wall et al. developed a balance prosthesis feeding back mediolateral head tilt measured by micromechanical sensors to the user through a vibrotactile display. More recently, Tyler et al. developed a head position-based, tongue-placed biofeedback system (see also several other studies) whose underlying principle is to transmit artificially sensed head orientation/motion with respect to gravitational vertical along anteroposterior and mediolateral axes through electrotactile stimulation of the tongue. Note that the tongue was chosen as a substrate for the electrotactile stimulation site according to its neurophysiologic characteristics. Indeed, because of its dense mechanoreceptive innervations and large somatosensory cortical representation, the tongue can convey higher resolution information than the skin can. In addition, because of the excellent conductivity offered by the saliva, electrotactile stimulation of the tongue can be applied with much lower voltage and current than is required for the skin. For instance, perception with electrical stimulation of the tongue is better than with fingertip electrotactile stimulation, and the tongue requires only approximately 3% (5–15 V) of the voltage and much less current (0.4–2.0 mA) than the fingertip. In a pioneering experiment, persons with bilateral vestibular dysfunction have been shown to efficiently use this tongue tactile sensory information to improve their head stabilization in space, indicating that they could substitute this augmented sensory information for the lack of vestibular sensory information to control head displacements. In the present study, we assessed the effectiveness of this head position-based, tongue-placed biofeedback system in providing sensory supplementation to preserve head stability in space in the absence of visual information.

METHODS

Subjects

Nine healthy young male university students (age, 23.4 ± 3.1 years; body weight, 71.9 ± 11.3 kg; height, 1.80 ± 0.11 m; mean ± SD) with normal vision and no history of motor problems, neck injury, vertigo, neurologic disease, or vestibular impairment voluntarily participated in the experiment. They gave their informed consent to the experimental procedure as required by the Declaration of Helsinki and the local Ethics Committee after the nature of the study had been fully explained.

Task and Procedures

Subjects, arms close to the trunk, stood barefoot, their feet placed in a semitandem position with the dominant foot spaced 4 cm before the other. The posture was chosen to enhance lateral instability of stance.

Each subject’s task was to sway as little as possible in two No Vision and Vision conditions. In the No Vision condition, they were asked to close their eyes. In the Vision condition, they were asked to fixate the middle of a visual target consisting of a black cross (20 × 25 cm) located 1.50 m away from them. This visual target was adjusted for the height of each subject so that its center was at eye level. These two conditions of No Vision and Vision were executed in two experimental conditions.

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Head Stabilization in Space and Sensory Supplementation

FIGURE 1. Sensory coding schemes for the Tongue Display Unit (right) as a function of the head orientation with respect to gravitational vertical (left): (1) Neutral, (2) right-side-tilted, (3) left-side-tilted, (4) flexed, and (5) extended head postures.

conditions of No Biofeedback and Biofeedback. The No Biofeedback condition served as a control condition. In the Biofeedback condition, subjects executed the postural task using a biofeedback system (BrainPort Balance Device; Wicab, Inc., Middleton, WI). This system consists of two principal components, the intraoral device (IOD) and the controller. On the one hand, the IOD is made up of an electrotactile array, a tether, and a microelectromechanical system (MEMS; 3-axis, ±2 g, digital output accelerometer; ST Microelectronics, Geneva, Switzerland). Electrotactile stimuli are delivered to the dorsum of the tongue by the electrode array, which is fabricated using industry-standard photolithographic techniques for flexible circuit technology and makes use of a polyimide substrate. All 100 electrodes (1.5-mm diameter, on 2.32-mm centers) on the 24 mm × 24 mm array are electroplated with a 1.5-μm thick layer of gold. The tether (12 mm wide × 2 mm thick) connects the electrotactile array and accelerometer to the controller. The MEMS accelerometer, mounted on the superior surface of the electrode array, senses head position along the anteroposterior and mediolateral directions. Both the accelerometer and the associated flex circuit are encapsulated in a silicone material to ensure electrical isolation for the subject. On the other hand, the controller contains an embedded computer (ColdFire MCF5249C [Freescale Semiconductor, Austin, TX], 120 MHz, 32-bit microprocessor), stimulation circuits, user controls, and battery power supply. Custom software operating on the controller converts head-tilt signals from the accelerometer in the IOD into a dynamic 2-wane operating on the controller converts head-tilt signals from the accelerometer in the IOD into a dynamic 2

Rate sensor data coupled with linear accelerometer data could offer a more precise measure of angular and linear displacement. In this application, however, it is not necessary as long as the stimulus displacement is in the correct direction (the direction of tilt).

Each subject kept the IOD in his mouth for the duration of the experiment (i.e., in both the No Biofeedback and the Biofeedback conditions). In the Biofeedback condition, subjects continuously perceived position and motion of a small “target” stimulus on the tongue display, corresponding to head orientation/motion with respect to gravitational vertical. Specifically, as illustrated in Figure 1, when the subject’s head swayed left, right, forward, and backward, the electrotactile stimulation on the tongue moved left, right, forward, and backward, respectively. Subjects were then asked to continuously adjust their head orientation and to maintain the stimulus pattern at the center of the display. Before the test, subjects performed practice trials with eyes closed and eyes open, with and without Biofeedback. The purpose of these practice trials was for the subjects to ensure that they had become familiar with standing with the postural stance and that they had mastered the relationship between the different head positions and lingual stimulations.

Five 20-second trials were conducted for each of the four conditions (Vision/No biofeedback, No vision/No biofeedback, Vision/Biofeedback, and No Vision/Biofeedback). The order of presentation of the 20 standing trials was randomized over subjects.

A system for the analysis of movement (Optotrak 3020; Northern Digital, Waterloo, ON, Canada) was used to record the displacements of an infrared-emitting marker placed on the head of each subject (os metzometer; 3D resolution at 2.25 m distance; 0.01 mm; http://www.ndigital.com/optotrak-techspecs.php). Signals were sampled at 100 Hz (12-bit A/D conversion) and low pass filtered with a second-order Butterworth (10 Hz).

Statistical Analysis

The means of the five trials performed in each of experimental conditions were used for statistical analyses. Analysis of variance (ANOVA) with repeated measures of all factors was applied to the data as follows: 2 Axes (Mediolateral vs. Anteroposterior) × 2 Biofeedback (No Biofeedback vs. Biofeedback) × 2 Visions (No Vision vs. Vision). Post hoc analysis (Neuman-Keuls) was performed whenever necessary. The level of significance was set at 0.05. Considering the influence of individual anthropometric characteristics on displacements of the head during unperturbed stance, analyses were conducted on nonnormalized measures and measures normalized compared with each subject’s squared height.55,10

RESULTS

Figure 2 illustrates representative head displacements from a typical subject recorded in the four experimental conditions of Vision/No Biofeedback (upper left panel), No Vision/No Biofeedback (upper right panel), Vision/Biofeedback (lower left panel), and No Vision/Biofeedback (lower right panel).
Nonnormalized Measures of the Head Displacements

Range of the Head Displacements. Results showed a main effect of Axis ($F_{(1,8)} = 10.85; P < 0.05$), yielding increased range of the head displacements along the mediolateral relative to the anteroposterior axis and a significant three-way interaction of Axis × Biofeedback × Vision ($F_{(1,8)} = 5.35; P < 0.05$; Fig. 3A). The decomposition of this interaction into its simple main effects indicated, along the mediolateral axis (left panel), that the No Vision condition yielded a larger range of head displacement than the Vision condition ($P < 0.001$) in the No Biofeedback condition, whereas no significant difference was observed in the Biofeedback condition ($P > 0.05$). Interestingly, in the No Vision condition, the availability of biofeedback allowed subjects to significantly reduce their range of head displacements to reach a level similar to that observed when vision was available (in Vision/Biofeedback and Vision/No Biofeedback conditions; $P > 0.05$). Along the anteroposterior axis (right panel), no significant difference between the No Vision and Vision conditions was observed ($P > 0.05$).

Standard Deviation of the Head Displacements. Results obtained for the SD of the head displacements were consistent with those obtained for the range of the head displacements. ANOVA showed a main effect of Axis ($F_{(1,8)} = 9.37; P < 0.05$), yielding increased SD of the head displacements along the mediolateral relative to the anteroposterior axis, and a significant three-way interaction of Axis × Biofeedback × Vision ($F_{(1,8)} = 6.29; P < 0.05$). As illustrated in Figure 3B, along the mediolateral axis (left panel), the No Vision condition yielded larger SD of the head displacements than the Vision condition ($P < 0.01$) in the No Biofeedback condition, whereas no significant difference was observed in the Biofeedback condition ($P > 0.05$). Interestingly, in the No Vision condition, the availability of the biofeedback allowed subjects to significantly reduce their SD of the head displacements to reach a level similar to that observed when vision was available (in Vision/Biofeedback and Vision/No Biofeedback conditions; $P > 0.05$).

Normalized Measures of the Head Displacements Relative to the Subject’s Squared Height

Range of the Head Displacements. Results showed a main effect of Axis ($F_{(1,8)} = 10.69; P < 0.05$), yielding increased range of the head displacements along the mediolateral relative to the anteroposterior axis and a significant three-way interaction of Axis × Biofeedback × Vision ($F_{(1,8)} = 6.20; P < 0.05$; Fig. 4A). The decomposition of this interaction into its simple main effects indicated, along the mediolateral axis (left panel), that the No Vision condition yielded a larger range of head displacement than the Vision condition ($P < 0.001$) in the No Biofeedback condition, whereas no significant difference was observed in the Biofeedback condition ($P > 0.05$). Interestingly, in the No Vision condition, the availability of the biofeedback allowed subjects to significantly reduce their range of the head displacements to reach a level similar to those observed when vision was available (in Vision/Biofeedback and Vision/No Biofeedback conditions; $P > 0.05$).
along the mediolateral axis (left panel), the No Vision condition yielded larger SD of the head displacements than the Vision condition \((P < 0.01)\) in the No Biofeedback condition, whereas no significant difference was observed in the Biofeedback condition \((P > 0.05)\). Interestingly, in the No Vision condition, the availability of biofeedback allowed subjects to reduce the SD of head displacements significantly to reach a level similar to that observed when vision was available \((in Vision/Biofeedback and Vision/No Biofeedback conditions; \(P > 0.05)\). Along the anteroposterior axis (right panel), no

**Standard Deviation of the Head Displacements.** Results obtained for the SD of the head displacements were consistent with those obtained for the range of the head displacements. ANOVA showed a main effect of Axis \((F_{(1,8)} = 11.86; \ P < 0.01)\), yielding increased SD of the head displacements along the mediolateral relative to the anteroposterior axis and a significant three-way interaction of Axis \(\times\) Biofeedback \(\times\) Vision \((F_{(1,8)} = 5.55; \ P < 0.05)\). As illustrated in Figure 4B,
significant difference between the No Vision and Vision conditions was observed \((P > 0.05)\).

**Discussion**

Without the provision of biofeedback (No Biofeedback condition), results showed different effects of the visual conditions on the head displacements according to the mediolateral and anteroposterior axes. Along the mediolateral axis, the Vision condition yielded decreased head displacements relative to the No Vision condition (Figs. 3A, 3B, 4A, 4B, left panels), whereas no significant difference was observed along the anteroposterior axis (Figs. 3A, 3B, 4A, 4B, right panels). Considering that the semitandem posture used in the present study induced larger head displacements along the mediolateral than the anteroposterior axis (Figs. 3, 4), this result supports previous observations of increased effects of visual information on head stabilization in space when the latter was challenged by normal aging \(^{17-19}\) disease, \(^{20-22}\) or experimental alteration of nonvisual sensory information in healthy young adults.\(^{15,22-24}\)

Conversely, when biofeedback was available (Biofeedback condition), results showed no significant difference between the No Vision and Vision conditions. Interestingly, this observation is valuable for nonnormalized measures and measures normalized relative to the subjects’ squared height, \(^{15,16}\) suggesting that the use of a tactile biofeedback system improved head stability during upright stance in the absence of vision. This result is consistent with the head tilt reduction previously reported when standing healthy young subjects used head tilt information from a vibrotactile display on the trunk.\(^7\) Interestingly, results of the present study further show that the availability of the biofeedback allowed subjects to reduce head displacements in the absence of vision significantly to reach levels similar to those observed when vision was available. In other words, subjects were able to use head position-based, tongue-placed biofeedback efficiently to suppress head instability induced by the suppression of vision. What is more, the observation of a stabilizing effect of the head along the mediolateral axis only—along the axis of the greatest head sway (Figs. 3A, 3B, 4A, 4B)—further suggests that the effectiveness of this biofeedback in preserving head stabilization in space depends on the magnitude of head displacements observed when the biofeedback was not available. Considering that the underlying principle of the biofeedback system was to transmit artificially sensed head orientation/motion with respect to gravitational vertical (normally provided by the vestibular system),\(^{25-26}\) these results also are consistent with the larger head displacements observed in the absence rather than the presence of vision, when vestibular information was disrupted in healthy subjects through the application of galvanic vestibular stimulation\(^{22-25}\) or by vestibular loss caused by abnormality or disease.\(^{20,21}\)

In conclusion, results of the present study demonstrate the effectiveness of head position-based, tongue-placed biofeedback in providing sensory supplementation to preserve head stability in space in conditions of absent visual information, indicating that this augmented sensory information could substitute for the absence of a visual spatial reference system. Because various physical and physiologic visual parameters, such as visual acuity,\(^{27}\) central and peripheral visual fields,\(^{27}\) and motion parallax,\(^{28}\) also have been shown to affect head stabilization in space, it could be interesting to evaluate whether the head position-based, tongue-placed biofeedback system could help preserve head stabilization in space in these modified visual conditions. In other respects, previous studies have demonstrated the effectiveness of various balance prostheses with the use of visual,\(^{29-31}\) auditory,\(^{32,33}\) vibrotactile,\(^{34}\) or electrotactile\(^{35,36}\) biofeedback in reducing postural sway. Whether the availability of the head position-based, tongue-placed biofeedback system allows healthy young persons to suppress the deleterious effects of visual withdrawal on upright postural stability also remains to be assessed. We believe that such investigations could strengthen the potential clinical value of this biofeedback system.

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**References**


