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Perception of slow pitch and roll body tilts in bilateral labyrinthine-defective subjects

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Abstract

The aim of the present study was to examine whether the perception of slow body tilts in total darkness was affected by a complete loss of vestibular function. Four blindfolded bilateral labyrinthine-defective subjects (LDs) and 12 normal subjects (Normals) were seated and immobilized with large straps against the back of a rotating L-shaped platform, and were passively displaced from the upright at $0.05°\cdot s^{-1}$ in the pitch and roll dimensions. Subjects were asked to detect the slow change in their body orientation, by indicating as soon as possible the direction of tilt. After a brief period of practice observed for all LDs at the beginning of the session, results showed no significant difference between LDs and Normals in the mean detection threshold recorded for each direction of tilt. The mean perceptual threshold was 4.4 versus 5.1° in the roll dimension, and 6.1 versus 6.1° in the pitch dimension, for the LDs and Normals, respectively. These findings indicate that the accurate perception of body orientation in quasi-static conditions is mainly allowed by somatosensory information rather than by otolithic inputs. © 2001 Elsevier Science Ltd. All rights reserved.

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1. Introduction

The vestibular apparatus is known as one of the prime sensory systems involved in the control of posture [15] and in the perception of body orientation [21]. Regarding vestibular implications during stance, it has been proposed that the otoliths cover low frequencies of sway (below 0.5 Hz), whereas semi-circular canals are much more sensitive to higher frequencies of oscillation [8,15,17]. Furthermore, considering the characteristics of the dynamic regulation of stance, Nashner [15] concluded that the otoliths play no part in the detection of normal body sway motion, but their information rather serves as a static vertical reference. Experiments with bilateral peripheral vestibular deficits have led to interesting results regarding the vestibular contribution to postural control. Indeed, it has been shown that complete labyrinthine-defective subjects (LDs) responded much more slowly to antero–posterior sway perturbation [1,16]. Such a decreasing performance in the control of dynamic stance was attributed to the alteration of the vestibulo–spinal reflex system controlling the stabilizing muscular responses following a rapid tilt of the body [1]. On the other hand, under static conditions in which posture was not disturbed, differences in performance among LDs and Normal subjects were relatively small, even with eyes closed [16]. This suggested that patients were efficient in using other sensory inputs such as somatosensory cues from the support surface for controlling their upright stance under fixed support surface conditions. More recently, it was demonstrated that the vestibular threshold for the perception of sway when standing still (0.57°) is many times greater than the proprioceptive threshold

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(0.12°) [9]. Furthermore, it has been shown that the threshold for the detection of a body tilt is much higher (6.5°) when proprioceptive information cannot be dynamically integrated [20]. These results suggested that, even for a very low frequency motion, otolithic cues did not contribute efficiently to the perception of slow changes in body orientation with respect to gravity. Conversely, somatosensory cues seem to be much more informative for perceiving a very slow body tilt. To further study this question, the present experiment investigated the extent to which patients with complete bilateral peripheral vestibular deficits are able to detect in the dark a slow change in their body orientation as quickly as normal subjects when somatosensory cues are available.

2. Methods

2.1. Subjects

Four LDs and 12 Normal subjects (mean age, 29 ± 6 years) without vestibular defect or any other neurological disorders participated in the study. All subjects were naïve as to the purpose of the experiment. In the following section, the characteristics of each LDs will be further discussed.

2.1.1. Case number 1 (chemical vestibular ototoxicity)

A female patient (BT), aged 60, was in treatment with chemotherapy for a non-Hodgkin's lymphoma, diagnosed 2-months earlier. The patient was treated by aminoglycoside antibiotics (amikacin) in one injection a day, 10 mg/kg per day for an urogenital infection. After the second injection of amikacin, the patient complained of acute vertigo and sensorineural hearing loss. The hearing thresholds were at 70 dB of loss in all frequencies, bilaterally. Clinical vestibular examination was not possible since the patient was obliged to bed rest because of strong vertigo and vomiting. The day after, the patient was able to stand up by aid of the physician. The Fukuda test was positive, with a deviation of 50°, with no specific right or left side by repeating the test several times.

2.1.2. Case number 2 (idiopathic areflexy)

A female patient (JJ), aged 52, had episodic vertigo since 5 years. Clinical examination did not find any nystagmus, neither on the head-shaking test, nor on the vibratory test. Pure tone audiogram indicated a slight sensorineural hearing loss on the right ear for high frequencies. Brain evoked response potentials (BERA) were of endocochlear type with normal wave latencies. Magnetic resonance imaging (MRI) was normal. Biological examination was normal too. The patient never suffered from neurological or general disease, and never took any ototoxic medication. The responses to the vestibular tests showed a total bilateral areflexy. In absence of any clear etiology, the clinical findings in this patient were described as an idiopathic vestibular bilateral areflexy.

2.1.3. Case number 3 (post-traumatic areflexy)

A male patient (FP), aged 41, was victim of a severe cranial and rachidial trauma in January 1998. The imaging showed a bilateral axial fracture of the petrous bone, with transection of the vestibular tract, responsible of bilateral deafness. In 1999, the patient was operated on a left cochlear implant, with a moderate good functional result on the hearing. The responses to the vestibular tests showed a total bilateral areflexy.

2.1.4. Case number 4 (post-surgical vestibular areflexy)

A male patient (ES), aged 37, presenting a neurofibromatosis of type 2 (NF2), which is a genetic disease characterized by the existence of a bilateral vestibular schwannoma, was operated on by a complete bilateral tumor removal in two stages. On the left side, the patient presented a tumor of grade III (3 cm) removed through a translabyrinthine approach on May 1999. This operation resulted of deafness and left vestibular areflexy. On the right side, tumor of grade II (2 cm) was removed via a retrosigmoid approach on June 2000 with the aim of hearing preservation. Post-operative pure-tone audiometry and speech audiometry showed no hearing loss on the right ear. The facial nerve function, observed on postoperative follow-up was normal on both sides. The surgical total removal of the tumors followed the principle of enlarged approach exposing both the internal auditory canal, the cerebellopontine angle, and the carefully section of the superior and inferior vestibular nerve with micro-scissors under a binocular operating microscope. Hence, the bilateral vestibular function was totally abolished surgically.

2.2. Vestibular tests

Several standardized clinical tests were performed in all four patients in order to assess the bilateral peripheral vestibular areflexy. The patients were investigated after the acute period in order to conduct the tests with no clinical complain of the patient (no vertigo, dizziness, illness, giddiness). Several quantitative rotational tests were performed to assess the response to the visual vestibulo–ocular reflex (ViVOR), the vestibulo–ocular reflex (VOR), the cervico–ocular reflex (COR). On the videonystagmography, the sequence ViVOR–VOR1–COR–VOR2 showed a typical response with a normal pattern of ViVOR, no response to the VOR, and high responses to the COR. The rotation head velocity test (Eritest) at low ($20° \cdot s^{-1}$) and high frequencies of stimulation (600°·s^{-1}) did not evidence any nystagmus by videonystagmoscopy. The caloric vestibular stimulations, performed with a calibrated temperature of hot (44 °C) and cold (30 °C) water, were negative on both right and left side. The Bárány test using water at 20 °C was also negative.

3. Apparatus

Subjects were seated against the back of a computer motorized L-shaped platform and were firmly attached to it with shoulder, hip and feet straps (Fig. 1). The head was immobilized through a padded grip device fixed to the seat. The platform generated very slow pitch and roll tilts, at a constant velocity of 0.05°·s^{-1} following an initial acceleration ramp of 0.005°·s^{-2}. Such slow displacements prevented from stimulating subjects' semi-circular canals [2,9]. The axis of rotation was approximately situated at the level of subjects' center of mass. Position signals from the platform were sampled at 20 Hz (12 bit A/D converter).

4. Task and procedure

Subjects' task was to detect a slow change in their body orientation with respect to gravity. Prior to each trial, subjects, restrained on the seat in total darkness, were oriented in an initial upright position (i.e. vertical head and trunk orientation with respect to gravity). When ready, the platform initiated its rotation. Subjects were asked to verbally indicate as soon as possible when they perceived a change in body orientation and the direction of their tilt. They were encouraged to give their response as soon as they reached a confidence level of 4 on a 5- points scale. Following the response, corresponding to the end of a trial, the platform was brought back to the starting position. In order to maintain the same level of attention and to avoid lassitude or fatigue, the experiment was divided into successive blocks of trials, with 5 min of rest between each block. Each block was composed of four tilt trials in pitching or rolling (two trials for each direction of tilt plus one catch trial with the platform remaining immobile for 4 s). Within a block, these trials were presented randomly. When an error of judgement was made, an additional identical trial was randomly inserted in the block. Therefore, subjects were neither told about the number of trials that composed a block, nor about the plane or direction of tilts. Normals were tested on two blocks (block 1: rolling; block 2: pitching). Since a practice effect was expected for LDs at the beginning of the session, they were tested on three successive blocks of trials, for which tilts of the first block were randomly repeated in the third block (block 1: pitching; block 2: rolling; block 3: pitching). A complete session lasted between 45 min and 1 h.

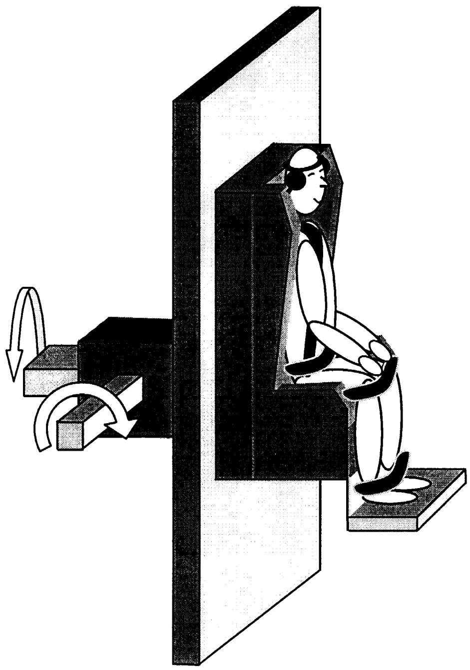

Fig. 1. Illustration of the experimental set-up. Subjects sat on a chair fixed onto the servo-assisted platform. They were firmly attached to prevent any movement of the body during tilts of the platform.

5. Results

5.1. Errors of judgement

Overall, Normals made judgement errors in 11 and 15.1% of the tilt trials in blocks 1 (rolling) and 2 (pitching), respectively. The rate of LDs' errors reached 25% of the tilt trials in the first block (pitching), but was quiet similar in proportion to that observed for the Normals in the following blocks (12.5% of errors in blocks 2 (rolling) and 3 (pitching) for LDs). For the catch trials, LDs tended to make more errors than Normals (25 vs. 8.3%, respectively). In all cases, the erroneous reported direction of tilt was different across trials and subjects.

5.2. Detection thresholds in LDs

Fig. 2 illustrates the performance measured for the single trials for each patient. A 4 subjects × 3 blocks of trials analysis of variance (ANOVA) applied to the single results of the four patients showed a main effect of the blocks of trials ($F_{(2,36)} = 19.49$; $P < 0.001$). A post hoc analysis (Scheffé test) showed that the threshold for the perception of tilt observed in block 1 was markedly higher than in blocks 2 and 3 (14.1° ± 3.4, 4.4° ± 0.5

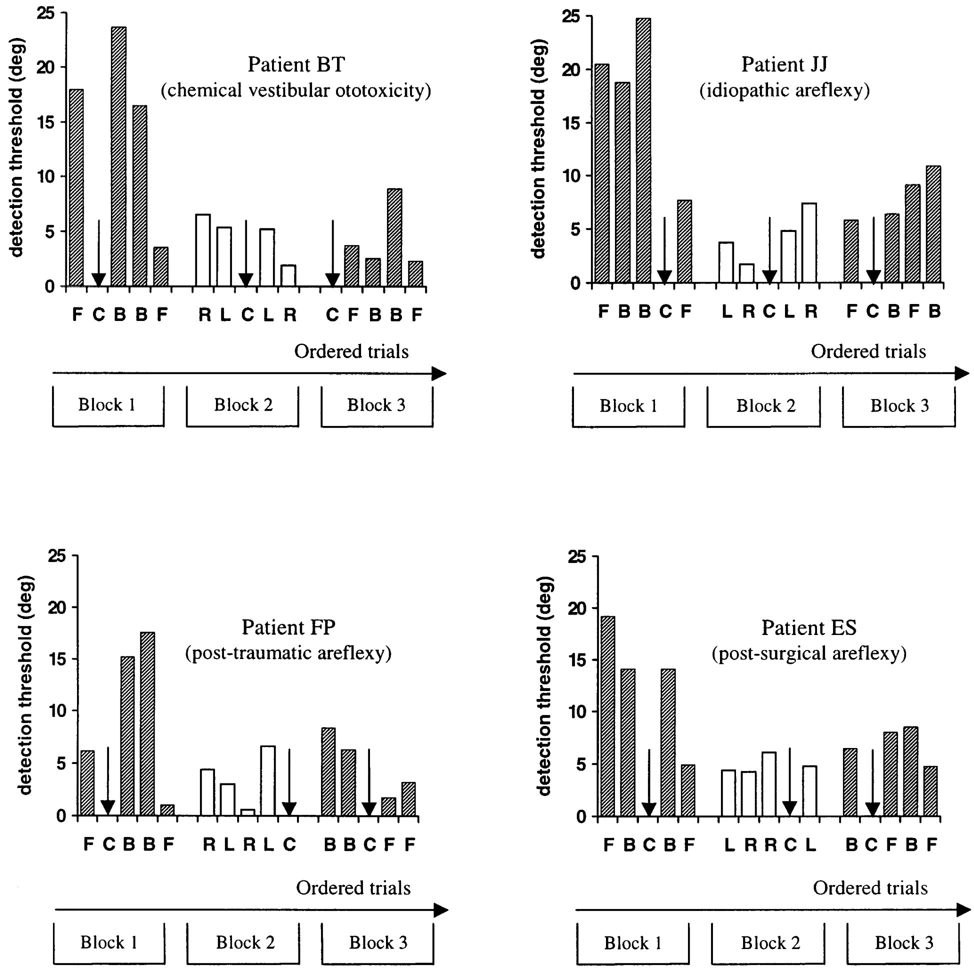

Fig. 2. Angular threshold for the perception of a body tilt starting from the vertical position for LDs during the 15 consecutive trials. Three blocks were presented. The first and last ones were composed of tilts in the pitch dimension (F, forward tilt; B, backward tilt), and the second one was composed of roll tilts (L, left side tilt; R, right side tilt). The arrows indicate the position of the catch trials (C), with the platform remaining immobile. Note the abrupt decrease of the detection threshold after the first three tilt trials for all the four patients.

and $6.1° \pm 1.5$, for blocks 1, 2 and 3, respectively, $P < 0.001$). As shown in Fig. 2, a rapid and sudden improvement, expressed in decreasing detection thresholds, took place similarly for each patient after the third tilt trial of the session. The ANOVA yielded no difference in the mean detection threshold for each subject ($F_{(3,36)} = 1.41$; $P > 0.1$). Furthermore, the interaction of subject × block was not significant ($F_{(6,36)} = 0.63$; $P > 0.1$). It is thus noteworthy that LDs' perceptual performance was very similar along the trials, while these subjects presented different etiologies.

5.3. Comparison between LDs and Normals

Regarding the Normals' results, observation of the data showed no practice effect for this group, contrary to what was observed for the LDs. In order to compare the LDs to the Normals, block 1 for the LDs was excluded from the comparative analysis. A 2 groups (Normals vs. LDs) × 2 directions of tilt (Rolling vs. Pitching) ANOVA with repeated measures on the last factor was applied to the mean detection threshold measured for each subject. Results showed a main effect of the direction of tilt ($F_{(1,14)} = 11.42$; $P < 0.01$). Subjects exhibited a lower mean detection threshold for roll than for pitch tilts. More interestingly, the ANOVA yielded no main effect of group ($F_{(1,14)} = 0.13$; $P > 0.1$), and no significant interaction between the two factors ($F_{(1,14)} = 1.01$; $P > 0.1$). As illustrated in Fig. 3, the mean detection threshold observed for the LDs and the Normals was not different for both the roll (block 1: $4.4° \pm 0.6$ vs. $5.1° \pm 1.6$ for LDs and Normals, respectively) and pitch tilts (block 2: $6.1° \pm 1.7$ vs. $6.1° \pm 2.3$ for LDs and Normals, respectively).

6. Discussion

This study investigated the perception of a slow change in body orientation starting from the vertical position, for subjects with a complete vestibular deficit. The difference between block 1 and the two following blocks in LDs' results, and more specifically, the decrease observed after the three initial tilt trials suggested a strong practice effect, which was not observed for the Normals in the same experimental conditions. Processes of improvement were found in several studies investigating the perceived orientation in patients with vestibular defects [6,7,12]. Different hypotheses can explain this phenomenon in the present study.

The first hypothesis implies that LDs, more than other subjects, need a period of habituation when discovering a new unusual environment. As it is known that LDs' behavior requires perceptual stability and regularity, it is not surprising to see them briefly disconcerted when facing a new task in a stressing dark room. Then, the initial improvement of LDs' perceptual judgement might only show that patients become accustomed to the environment and task.

The second hypothesis assumes the existence of a sensory adaptive process developed by LDs. Recent models of intersensory interactions [11,18] assumed that the combination of multiple sensory inputs allows to reduce the probability of errors in correctly orienting the body with respect to gravity. In LDs, sensory redundancy or complementarity between visual and somatosensory cues are highly important to compensate for the loss of vestibular information. In absence of visual information, LDs have to scan for the sensory channel, which is able to convey informative cues, that is, somatosensory inputs. In that condition, the remaining sensory information has to be recalibrated and updated, so that the somatosensory signals can take a clear behavioral significance for perceiving body orientation [3]. As this process might not occur immediately, it could be at the origin of the improvement period observed during the first three tilt trials of the present experiment.

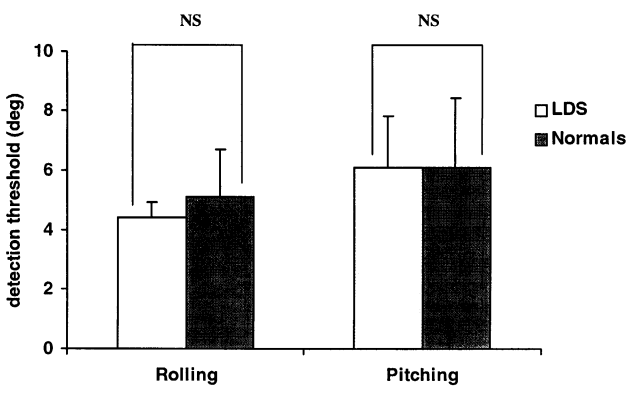

Fig. 3. Mean detection threshold and standard deviation for the LDs and Normals for pitching and rolling. No significant difference was found between LDs and Normals.

The primary finding of this study is that, following this short period of improvement, no significant difference was found for the mean detection threshold observed in LDs and Normals for the two planes of tilt. The main effect of the direction of tilt found in this experiment, that is, a higher detection threshold in pitching than in rolling, confirmed results of other studies [3,5,20], and was early discussed in the paper of Teasdale et al. [20]. The absence of effect between the two groups clearly showed that subjects without vestibular function are still able to perceive a very slow change of their body orientation in complete darkness, as well as normal subjects, provided that somatosensory cues are still available. These results confirmed that somatosensory information has a prominent role for estimating body orientation. In earlier studies, it was demonstrated that when LDs had to perceive their body verticality, their mean judgements were as accurate as for normal subjects [3]. This suggests that the somatosensory system can provide an essentially accurate mean estimate of body verticality [5], in spite of a loss of sensibility, as shown by a larger angular sector of subjective uprightness [3] or by a higher variance in postural vertical estimates [6]. Other experiments confirmed the predominant influence of somatosensory cues on LDs' judgements of spatial orientation. Nakamura and Bronstein [14] found that the perception of head angular displacement upon the stationary trunk, involving neck proprioceptive stimulation, was identical to that of normal subjects. Furthermore, for a lower range of motion stimuli (below 0.1 Hz for a $\pm 8°$ angular displacement), the perception of 'head in space' following a head rotation on the stationary trunk can be improved in LDs by allowing them to hold a stationary bar with one hand, that is, by providing them a somatosensory reference [19]. Great implications of somatosensory information were also found in LDs' regulation of stance. For instance, when giving LDs light contact cues on the fingertip, their postural sway during a static posture was reduced [13]. On the other hand, when disturbing proprioceptive inputs by moving the support surface during stance, LDs were dramatically impaired in their ability to maintain stability as compared with normal subjects [16]. More generally, the alteration of relevant somatosensory inputs has also severe repercussions in normal subjects' body orientation. Recent experiments showed that the detection threshold for slow body tilts was greatly impaired, when gravity based somatosensory cues were disturbed by immobilizing subjects with large straps against a rotating platform (i.e. by inhibiting dynamic proprioceptive information about body orientation [20]) or by immobilizing the subjects in a specific device looking like a body cast (i.e. by attenuating specific patterns of tactile and proprioceptive information about body orientation [4]). In the latter case, threshold for the detection of a body tilt starting from a vertical position reached 15.8°.

Results also showed that the availability of vestibular inputs does not imply a better perception of body orientation in such a task. From an electrophysiological point of view, it is known that slight modifications of head orientation in subjects without vestibular defect lead to modulations of the otolith afferents discharge [10]. In the present experiment, however, when subjects were tilted at $0.05°\cdot s^{-1}$, it may be advanced that the speed of variation of the otolithic signal through time was not sufficiently high to take behavioral significance. These findings suggested that the otolith organs cannot be considered as efficient graviceptors in quasi-static conditions [20]. The vestibular inputs may become much more useful only when the signal to noise ratio reaches an unambiguous level, such as for more dynamical situations (e.g. for more rapid tilts), or with trained subjects, such as gymnasts [4].

In summary, the most striking result of the present study was that, after a short period of improvement, LDs were able to detect a slow change in their body orientation in total darkness, as well as normal subjects, mainly through somatosensory cues. It confirmed the major influence of somatosensory inputs in the perception of body orientation, and illustrated the great importance that these inputs can have for LDs in their everyday life.

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