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Influence of pitch tilts on the perception of gravity-referenced eye level in labyrinthine defective subjects

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Abstract

We investigate the role of vestibular information in judging the gravity-referenced eye level (i.e., earth-referenced horizon or GREL) during sagittal body tilt whilst seated. Ten bilateral labyrinthine-defective subjects (LDS) and 10 age-matched controls set a luminous dot to their perception of GREL in darkness, with and without arm pointing. Although judgements were linearly influenced by the magnitude of whole-body tilt, results showed no significant difference between LDS and age-matched controls in the subjective GREL accuracy or in the intra-subject variability of judgement. However, LDS performance without arm pointing was related to the degree of vestibular compensation inferred from another postural study performed with the same patients. LDS did not utilize upper limb input during arm pointing movements as a source of graviceptive information to compensate for the vestibular loss. The data suggest that vestibular cues are not of prime importance in GREL estimates in static conditions. The absence of difference between controls and LDS GREL performance, and the correlation between the postural task and GREL accuracy, indicate that somatosensory input may convey as much graviceptive information required for GREL judgements as the vestibular system.

Keywords: Vestibular defect; Body orientation; Frame of reference; Egocentric; Geocentric

1. Introduction

The vestibular system is a key sensor for the perception of head and body orientation in space (Green & Angelaki, 2004; Schöne, 1964). Nevertheless, previous studies showed that the perception of body orientation was not impaired in labyrinthine-defective subjects (LDS) (Bringoux et al., 2002; Bronstein, 1999). Mean estimates of the subjective postural vertical (SPV) in LDS were identical to those performed by normal subjects, although a decreased sensitivity in the judgements was noted. On the other hand, artificial removal of gravity-based somatosensory information or pathological somatosensory impairment yielded strong modifications in SPV or body tilt judgements (Anastasopoulos, Bronstein, Haslwanter, Fetter, & Dichgans, 1999; Bringoux, Nougier, Barraud, Marin, & Raphel, 2003). The present study investigates whether vestibular cues are of prime importance in an estimation task for which body orientation must be taken into account, namely judging the gravity-referenced eye level (GREL).

GREL can be defined as the "earth horizon", that is the trans-ocular plane normal to the direction of gravity (Bringoux, Tamura, Faldon, Gresty, & Bronstein, 2004; Stoper & Cohen, 1989). It is known to be involved in distance (Ooi, Wu, & He, 2001) and location (Li, Dallal, & Matin, 2001) specification of visual targets seen in otherwise darkness, and its false perception may have critical repercussions in modern transportation (e.g., aeronautics). In a GREL estimation task, one must perceive an external gravity-referred direction (geocentric component), which has to be linked with eye level (egocentric component). Therefore it can be considered a "semi-geocentric" task.

GREL estimates are linearly dependent on pitch body tilt angle, that is lowered with forward tilt and elevated with backward tilt (Bringoux et al., 2004). Although this "body tilt effect" can be interpreted in terms of body tilt underestimation (according to classical explanations of the Aubert effect for

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the subjective visual vertical or SVV; Lechner-Steinleitner, 1978), the difference between SVV and SPV settings reported in the literature may suggest another interpretation, based on an egocentric shift (Bringoux et al., 2004). According to this hypothesis, subjects tend to rely more on an egocentric component when tilted (in line with the idiotropic vector hypothesis; Mittelstaedt, 1983, 1999), and thus shift GREL judgements towards the head-referenced eye level (HREL), namely the trans-ocular plane normal to the transverse plane of the head (i.e., a purely egocentric reference; Stoper & Cohen, 1989).

As this egocentric shift can be only counteracted by geocentric cues, one might expect a more pronounced egocentric shift for LDS, since the vestibular apparatus is involved in the perception of the direction of gravity. On the other hand, if LDS and normal subjects both used predominantly non-vestibular cues to estimate the geocentric component, then there should be no difference in GREL judgements for the two groups.

Additional gravitational cues, e.g., from the generation of gravitational torques around the arm joints when using arm movements (Gentaz & Hatwell, 1996), could also assist subjects in perceiving their orientation with respect to gravity (Fitger, 1976; Luyat, Gentaz, Regia-Corte, & Guerraz, 2001). However, the 'body tilt effect' on GREL in normals is increased when arm-pointing movements are used in addition to visual cues (Bringoux et al., 2004). This incoherence has been explained as an increased egocentric shift associated with the use of arm movements, which obscures any graviceptive function of arm inputs for normal subjects (Bringoux et al., 2004). However, in LDS, the graviceptive sensitivity of arm lifting could be increased in order to compensate for the lack of vestibular information.

Two experimental sessions involving LDS and age-matched controls (AMC) were carried out in order to test these hypotheses. The first one required subjects to estimate their GREL visually, without performing any arm movements. The second session, based on visual GREL settings performed through arm pointing movements, investigated the putative role of dynamic graviceptive signals arising from arm movement (i.e., dynamic gravitational torque; Fitger, 1976; Luyat et al., 2001) after loss of labyrinthine function.

2. Materials and methods

2.1. Subjects

Ten bilateral LDS (six males and four females, mean age: 56 ± 9.2 y.o.) and 10 AMC (5 males and 5 females, mean age: 57 ± 9.8 y.o.) gave informed consent to participate in the study, according to local ethic committee guidance and ethical standards laid down in the Declaration of Helsinki. Absence of vestibular function was documented with bithermal caloric ear irrigation (30 and 44 °C) and horizontal rotational in the dark (velocity steps of $\pm 60^\circ\,s^{-1}$). Patients were tested in their chronic phase in order to avoid the influence of any disturbing manifestations such as vertigo or dizziness inherent to the acute phase. Table 1 summarizes the LDS' clinical data.

2.2. Apparatus

A fully detailed description of the experimental materials and methods can be found in a previous paper (Bringoux et al., 2004). The subjects were seated and tightly restrained in a padded chair which could be rotated in pitch, about a horizontal axis. The height of the chair could be adjusted so that the subjects' trans-ocular axis coincided with the axis of rotation. The velocity of the pitch rotation was set at $1.5^\circ\,s^{-1}$, with initial accelerations and final decelerations ($1.5^\circ\,s^{-2}$) above the semi-circular canals' thresholds for rotation perception (Fitzpatrick & McCloskey, 1994). The subject's head was firmly restrained by a headrest and a chinrest fixed to the chair frame, in order to keep it in line with the body at all times (Fig. 1).

GREL judgements were performed under two conditions: vision alone (GREL-V) and vision with pointing (GREL-VP). In 'GREL-V', a laser pointer was mounted on an earth-fixed motorized support and the height of the projected laser beam was adjusted via a hand-held dial. In the 'GREL-VP' condition, the laser pointer was fixed onto the subject's index finger with adhesive tape and they used arm pointing movements to indicate their visual perception of GREL. In both conditions the laser beam was projected onto a vertical board in front of the subject. This board was marked with a grid in Fick coordinates (i.e., angular projections onto the plane surface) and the position of the dot on the grid was recorded by the experimenter. In the 'GREL-V' condition, a potentiometer independently recorded the laser position, thus, providing confirmation of the reliability and validity of the experimenter's observations. A dim blue light diffused in the experimental room allowed recordings of the dot position relative to the grid. Subjects wore blue filter goggles, so they could not see anything else except the adjustable dot. The resolution of the apparatus enabled a measurement accuracy ranging from 0.05° with the potentiometer to 0.2° with experimenter's observations.

2.3. Task and procedure

The subject's task was to judge their subjective GREL in darkness. This was defined as the plane passing through the eyes, which is always normal to

Table 1
Information about the bilateral labyrinthine-defective patients tested

Patient ID	Age/sex	Time since presentation (years)	Aetiology	Testing	
				Calorics[a]	Rotation[b]
P1	67/F	5	Idiopathic	Not done	No response
P2	59/F	>12	Idiopathic	Not done	No response
P3	48/M	12	Idiopathic	No response	No response
P4	47/M	10	Idiopathic	No response	No response
P5	51/F	16	Idiopathic	Not done	No response
P6	59/M	>10	Meningitis	Not done	No response
P7	42/F	6	Idiopathic	No response	No response
P8	70/M	>3	Gentamicin[c]	Not done	No response
P9	52/M	>1	Idiopathic	Not done	No response
P10	63/M	8 weeks	Gentamicin[c]	Not done	No response

[a] Bilateral caloric irrigation (30 and 44 °C) with and without visual fixation.
[b] Electro-oculography during velocity step rotations in the dark of at least $\pm 60^\circ\,s^{-1}$.
[c] Gentamicin ototoxicity.

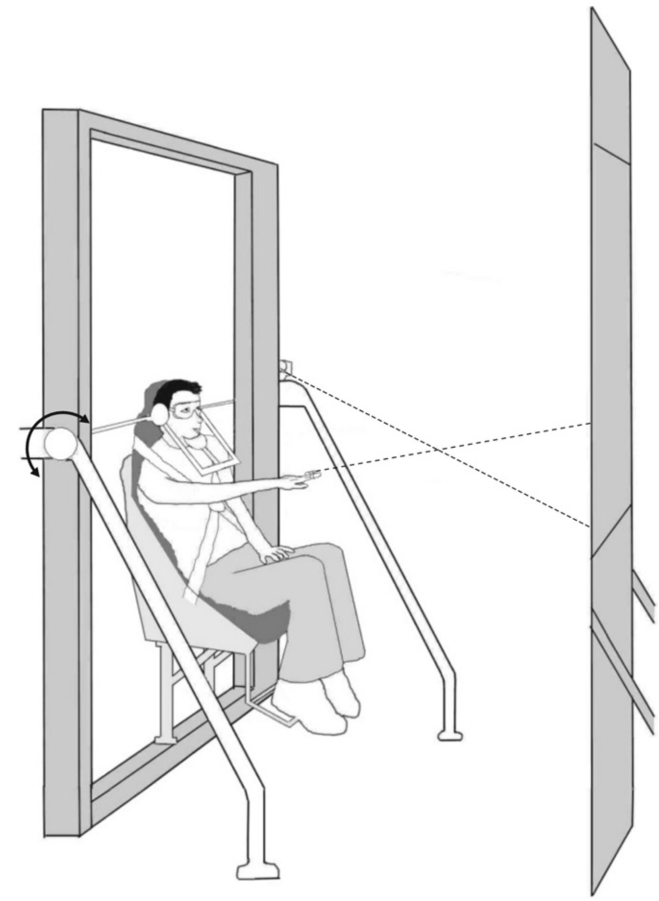

Fig. 1. Illustration of the setup with the two experimental conditions tested. The motorized chair rotated around the subjects' inter-ocular axis. The dotted lines illustrate the laser beam projected from an earth-fixed position for GREL-V and from the subject's index finger for GREL-VP.

gravity (i.e., parallel to the floor) and explained in lay terms as the perceived horizon, which could be thought of as "where the sky meets the sea". Drawings illustrating the experimental conditions and the objective GREL plane with tilted subjects were shown to avoid any ambiguity.

The experimental conditions were presented in two separate sessions and the order of the sessions was randomized. In Session 1, the subjects had to perform the task under purely visual control, without arm movements, by setting the height of the laser dot via a remote control dial (GREL-V). In Session 2, subjects used natural arm pointing movements to project the laser dot towards their perceived GREL (GREL-VP). Subjects were asked to concentrate on the visual dot location rather than on arm position. Six whole-body pitch orientations were deployed (upright; backward tilts of 10°, 20°, 30°; forward tilts of −10°, −20°). A session began and ended in the "upright" position. During the session, the sequence of pitch orientations was randomized, and subjects were returned to upright for 20 s before each new tilt angle. Once tilted, the subjects waited 20 s (allowing semi-circular canal effects to settle down) before being asked to perform their first setting. Six GREL estimates were obtained for each orientation (within a time period of 1 min). Subjects were told to close their eyes before and after each setting and, in the GREL-VP condition, to lower their arm to a resting position. In the GREL-V condition, the experimenter repositioned the visual target to a random location before each GREL-V setting, while the subject's eyes were closed.

2.4. Data analysis

Mean comparisons between groups or experimental conditions were performed with analyses of variance (ANOVAs), when data were distributed normally with comparable variance. Non-parametric analyses (Mann–Whitney *U*-tests for independent samples and Wilcoxon tests for dependant samples) were conducted when the assumption of normality and homogeneity of variance among groups was violated (see Table 2 for details). Statistical power of all parametric comparisons of means was also calculated. Distribution of GREL settings relative to the angle of body tilt was analysed through simple linear regression analyses. The relationship between LDS postural stability, reflecting the degree of vestibular compensation (Szturm, Ireland, & Lessing-Turner, 1994), and LDS performance in the GREL judgement task was also investigated. Postural sway data from an independent study was available for seven of our patients (Bunday & Bronstein, 2004). Postural sway (trunk displacement) had been recorded while the subjects stood on a moving platform (the MOVING condition in the "broken escalator" paradigm, Reynolds & Bronstein, 2003, 2004). The relationship between variables was assessed using a Pearson's correlation coefficient analysis.

3. Results

3.1. GREL estimates in upright orientation

Subjective GREL estimates performed in an upright orientation were lower than the physical GREL for both groups and conditions (mean position: −2.2°). A two groups (AMC versus LDS) × two conditions (GREL-V versus GREL-VP) ANOVA revealed no significant difference between groups ($F_{1,18} = 0.14$; $p > 0.05$, n.s.) or conditions ($F_{1,18} = 0.53$; $p > 0.05$, n.s.), and no

Table 2
Test of normality (Shapiro–Wilk test) and variance homogeneity (Levene's test) for subsequent mean comparison analyses

Normality	GREL estimates when upright		Slope coefficients		Intercept values		Intra-subjects variability	
	W	*p*	*W*	*p*	*W*	*p*	*W*	*p*
GREL-V: AMC	0.96	0.78	0.95	0.63	0.97	0.85	0.94	0.58
GREL-VP: AMC	0.96	0.74	0.96	0.73	0.93	0.45	0.95	0.72
GREL-V: LDS	0.88	0.15	0.95	0.69	0.99	0.99	*0.82*	*0.03**
GREL-VP: LDS	0.92	0.33	0.96	0.76	0.96	0.81	0.87	0.11

Variance homogeneity	GREL estimates when upright		Slope coefficients		Intercept values		Intra-subjects variability	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*
GREL-V: AMC vs. LDS	0.08	0.78	0.76	0.40	0.53	0.48	*6.94*	*0.02**
GREL-VP: AMC vs. LDS	0.00	0.96	0.17	0.68	0.24	0.63	*11.04*	*0.004**

* Significance ($p < 0.05$) means violation of normality or variance homogeneity assumption required for parametric analyses.

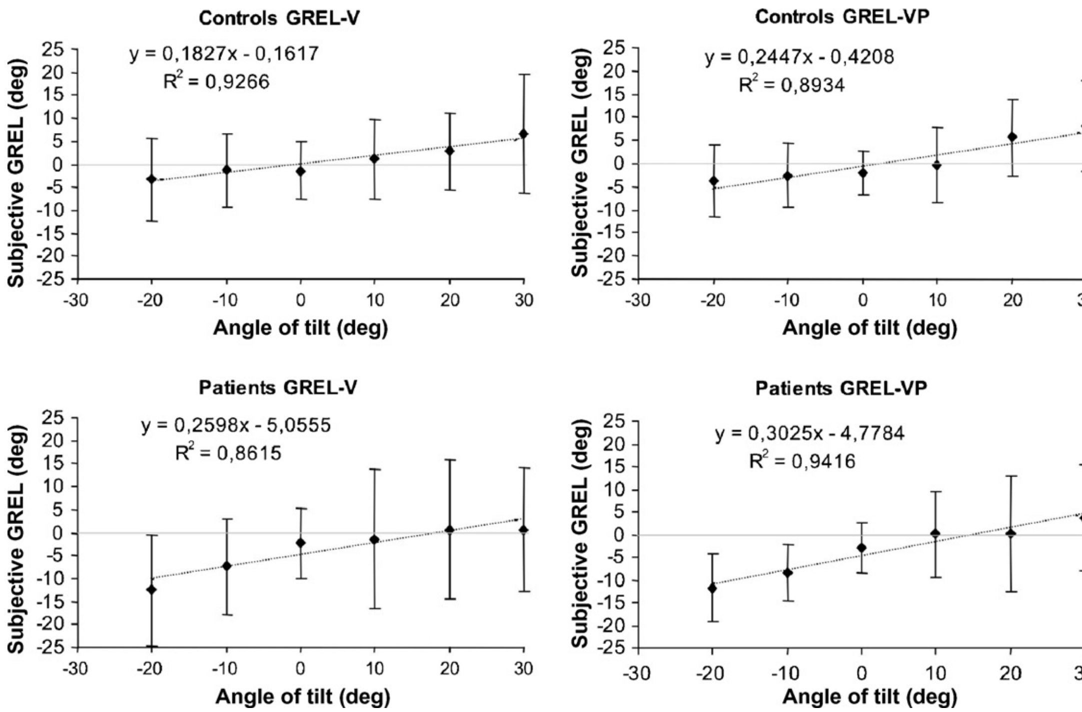

Fig. 2. Mean perceived GREL as a linear function of whole-body tilt for both groups of subjects and both experimental conditions. Negative angles of tilt correspond to forward tilts, whereas positive angles of tilt correspond to backward tilts. Negative GREL values indicate settings below physical GREL whereas positive GREL values indicate settings above physical GREL. Error bars represent standard deviation from the mean. The slope coefficients of the linear regression trend lines, representing the strength of the "body tilt effect", i.e., the shift of GREL estimates towards the body tilt, were not statistically different between groups and conditions.

interaction between these two factors ($F_{1,18} = 0.001$; $p > 0.05$, n.s.) in the absence of whole body tilt.

3.2. GREL estimates when tilted

In order to examine whether there was a linear relationship between subjective GREL and the angle of whole-body pitch tilt, a linear regression analysis was applied to the mean individual GREL estimates recorded in the six body orientations for both experimental conditions. The results showed a significant linear influence of the angle of tilt in both experimental conditions for AMC (GREL-V [$F_{1,58} = 7.54$; $p < 0.01$]; GREL-VP [$F_{1,58} = 17.95$; $p < 0.001$]) as well as for LDS (GREL-V [$F_{1,58} = 7.81$; $p < 0.01$]; GREL-VP [$F_{1,58} = 19.69$; $p < 0.001$]). GREL estimates were lowered with forward tilts and elevated with backward tilts (Fig. 2).

In order to study the magnitude of the linear body tilt influence upon GREL estimates, a two groups (AMC versus LDS) × two conditions (GREL-V versus GREL-VP) ANOVA was applied to the slope coefficients calculated for each individual regression line. This revealed no significant difference between groups ($F_{1,18} = 0.41$; $p > 0.05$, n.s.) and conditions ($F_{1,18} = 1.81$; $p > 0.05$, n.s.) and no interaction between these two factors ($F_{1,18} = 0.06$; $p > 0.05$, n.s.). The magnitude of the "body tilt effect" seemed then not to differ between AMC and LDS and between estimates assessed by vision alone or by vision with pointing movements (Fig. 2). In addition, we compared the mean intercepts obtained from each linear regression lines by a two groups (AMC versus LDS) × two conditions (GREL-V versus GREL-VP) ANOVA. It showed no significant difference between groups ($F_{1,18} = 2.36$; $p > 0.05$, n.s.) and conditions ($F_{1,18} = 0.03$; $p > 0.05$, n.s.) and no interaction between these two factors ($F_{1,18} = 0.19$; $p > 0.05$, n.s.). The mean "baseline" of the effect was not different between AMC and LDS and was not affected by the condition of assessment (Fig. 2). Nevertheless, results presented above were characterized by weak statistical power indices, mainly due to high variability in subjective responses between subjects. Table 3 summarizes the main statis-

Table 3
Level of significance (p) and statistical power ($1 - \beta$) for parametric mean comparison analyses

Factor	GREL estimates when upright		Slope coefficients		Intercept values	
	p	$1 - \beta$	p	$1 - \beta$	p	$1 - \beta$
Group (AMC vs. LDS)	0.72	0.06	0.53	0.09	0.14	0.31
Condition (GREL-V vs. GREL-VP)	0.47	0.11	0.20	0.25	0.86	0.05
Group × condition	0.98	0.05	0.80	0.06	0.67	0.07

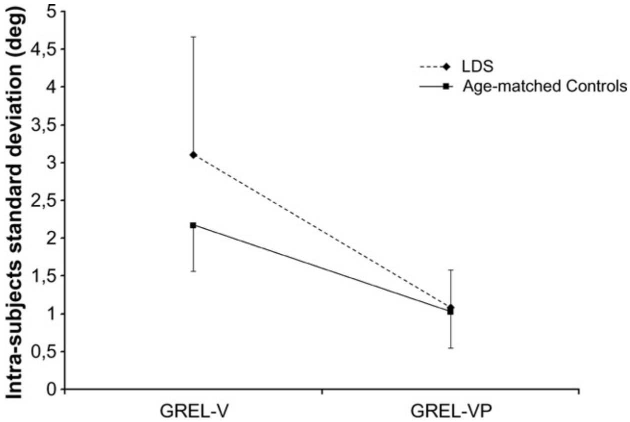

Fig. 3. Mean intra-subject variability for both groups of subjects and both experimental conditions. Error bars represent standard deviation from the mean.

tical outputs from parametric statistics about mean comparisons conducted in this study.

3.3. Intra-subjects variability on GREL estimates

Non-parametric statistics were used to analyse the intra-subjects variability, as preliminary tests revealed a violation of the assumption of normality and variance homogeneity between groups (Table 2). Mann–Withney *U*-test (comparing AMC versus LDS) and Wilcoxon test (comparing GREL-V versus GREL-VP conditions) were conducted on the mean intra-subjects standard deviations of individual GREL estimates. The results showed a main effect of the experimental condition for AMC ($T=0$; $p<0.01$) as well as for LDS ($T=3$; $p<0.05$) but no main effect of group, neither in GREL-V condition ($U=32$; $p=0.17$) nor in GREL-VP condition ($U=37$; $p=0.33$). Intra-subject variability was lower when visual GREL was assessed through arm pointing movements (Fig. 3).

3.4. Relationship between vestibular compensation and GREL estimates for LDS

Preliminary analyses did not show any relationship between the “body tilt effect” on GREL estimates and the time since presentation of all the patients tested ($r=-0.10$, $p=0.78$ in GREL-V condition; $r=-0.09$, $p=0.80$ in GREL-VP condition). Nevertheless, we aimed at investigating the influence of vestibular compensation and GREL perception. The relationship between LDS performance in the GREL task and in a postural condition reflecting an indice of their vestibular compensation was then tested in seven patients (see Section 2). A Pearson’s correlation coefficient analysis revealed a significant negative correlation between body sway amplitude and the GREL-V slope coefficients ($r=-0.78$, $p<0.05$). The more the patients swayed after walking onto a moving platform, the less they were influenced by body tilt when assessing GREL by vision alone (Fig. 4A). No significant linear relationship was found between body sway amplitude and the GREL-VP slope coefficients ($r=0.29$, $p=0.52$; Fig. 4B).

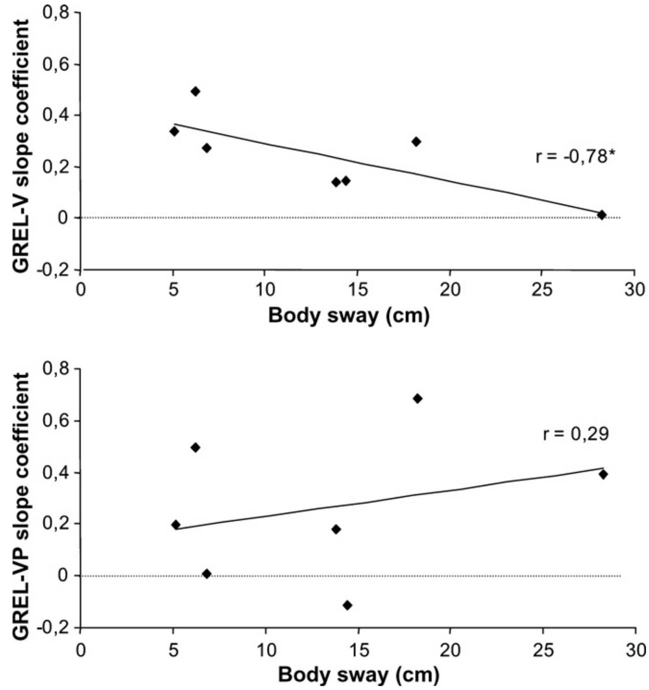

Fig. 4. Relationship between the GREL slope coefficients, i.e. the magnitude of the “body tilt effect” upon GREL estimates, in seven LDS and the maximum body (trunk) sway when walking on a moving platform (Reynolds & Bronstein, 2003, 2004). (A) Significant linear negative correlation between body sway and GREL settings performed with vision alone; (B) non-significant relationship between body sway and GREL settings performed through arm movements.

4. Discussion

The main purpose of the present study was to address the question of vestibular influence in the judgement of a semi-geocentric reference, such as the gravity-referenced eye level (GREL), for which the head orientation with respect to gravity must be taken into account (Bringoux et al., 2004; Stoper & Cohen, 1989). The otoliths are known to be the relevant vestibular organs for gravity sensing. Although the otoliths were not examined directly in our subjects (as otolith tests are cumbersome and often inconclusive), available clinical and pathological data indicates that disorders seriously involving the semi-circular canals regularly cause serious damage to the otoliths as well (Lempert, Gianna, Gresty, & Bronstein, 1997). This is confirmed by our previous study investigating body tilt effects on the subjective visual vertical in a similar group of LDS, which showed large differences between LDS and normal controls (Bronstein, Yardley, Moore, & Cleeves, 1996).

The results obtained in the upright position, both in patients with complete vestibular failure (LDS) and age-matched controls (AMC), are in line with previous reports of judgements of GREL being lower than the physical GREL (Raphel & Barraud, 1994; Stoper & Cohen, 1986). For body tilts between 30° backward and 20° forward, our results also confirm the linear relationship between the angle of tilt and GREL estimates, called the “body tilt effect” (Bourdin et al., 2001; Bringoux et al., 2004). GREL settings are lowered with forward tilts and elevated with backward tilts, a finding which may have repercussions on spatial orientation when subjects are tilted in an impoverished visual environment (Bringoux et al., 2004; Schöne, 1964). An explanation for this phenomenon invokes the presence of an "egocentric shift" towards the subjects' own longitudinal axis (for further details, see Bringoux et al., 2004), in line with the idiotropic vector hypothesis for roll tilts in visual vertical settings (Mittelstaedt, 1983, 1999). The magnitude of this egocentric shift is reflected in the mean slope coefficients calculated from each individual linear regression lines.

4.1. Vestibular defect and GREL judgement

The major finding of the present study is the unexpected lack of a significant difference in the mean slope coefficients between age-matched controls and LDS (Fig. 2). Intact otolith organs would be expected to counterbalance, to some extent, the egocentric shift exerted by pitch body tilt (the "body tilt effect"). This type of effect has been shown when visual vertical measurements during large roll body tilts have been compared in normal controls and LDS (large increase in 'A' effect seen in LDS, Bronstein et al., 1996). The range of body tilt in our study was anatomically limited (e.g. eyebrows restrict the visual range for perceiving the physical horizon). It is then possible that larger tilts could yield different results, like those obtained in the visual vertical experiments (Bronstein et al., 1996). Moreover, the weak power of our statistical analyses (Table 3) makes us remain cautious about the hypothesis of a strict equivalence between the LDS and AMC groups.

Nevertheless, the present finding puts into question a major vestibular contribution to the perception of static head and body tilts when other sensory cues are available. Earlier studies have already reported no difference in the perception of the subjective postural vertical (SPV) between normal subjects and LDS, after a very short adaptive period (Clark & Graybiel, 1963a, 1963b). This was recently confirmed by Bronstein (1999) who showed that the mean position of SPV was normal in LDS, despite a decreased sensitivity of judgement. In the same vein, Ito and Gresty (1997) found that LDS performed similarly to normals in estimating postural orientations in the pitch plane and Bringoux et al. (2002) showed that mean thresholds for the detection of body tilt for LDS and normals do not differ.

One might explain these results by a sensory reweighting process taking place after the vestibular deficit (Creath, Kiemel, Horak, & Jeka, 2002). As patients compensate, they progressively rely more on somatosensory inputs to ensure graviceptive function (Clark & Graybiel, 1966). This interpretation is supported by the finding of a significant negative correlation between LDS' body sway in a challenging postural task (the MOVING condition in the "broken escalator paradigm" (Reynolds & Bronstein, 2003, 2004), and visual GREL judgements (Fig. 4A). The patients who sway less might have learned to use mainly somatosensory cues for postural equilibrium. These more "somatosensory" patients would be more influenced by somatosensory adaptation when tilted (Bisdorff, Wolsley, Anastasopoulos, Bronstein, & Gresty, 1996); Clark & Graybiel, 1966; Higashiyama & Koga, 1998), in turn leading to an enhanced egocentric shift in GREL estimates. More work is needed in order to confirm this differential GREL behaviour depending on the recovery status of the patients, although important differences in visual and somatosensory dependence in patients with vestibular lesions are well documented (Guerraz et al., 2001).

The intra-subjects variability (i.e., the level of consistency in settings for a given subject), was also found to be similar between LDS and age-matched controls (Fig. 3). This result further confirmed the limited role of the vestibular system in GREL judgements, for which the "reproducibility" of estimates seemed not to be affected by the lack of vestibular information. In agreement, Clark and Graybiel (1967) have previously reported no significant difference between normals and LDS for "average errors" (i.e., variable errors) in a visual horizontal task during roll body tilts.

4.2. Influence of arm movements in GREL judgement

The second important result of the present study is the absence of influence of the experimental condition upon GREL judgements as well as the absence of interaction between the group of subjects and the experimental condition. Setting GREL via arm pointing movements neither diminished nor increased the "body tilt effect", and LDS responded similarly to age-matched controls whatever the method of assessment (Fig. 2).

Additional arm gravitational cues offered by arm lifting have been found to be helpful for tasks defined in a purely geocentric frame of reference such as the haptic assessment of the subjective vertical (Luyat et al., 2001) or the subjective zenith (Mittelstaedt, 1983). Our GREL-VP task differs from the former ones in that it also involves an egocentric component (i.e., eye level). Contrary to our previous findings in younger adults (Bringoux et al., 2004), we did not find an increased egocentric shift when judgements were performed via arm pointing movements. The higher mean slope coefficient and increased inter-subject variability recorded in GREL-V condition for the older LDS and age-matched controls tested in this study might explain this apparent contradiction. In view of the weak power of our statistics, here again, it is more prudent to report an absence of significant differences rather than absolute similarity between the LDS and AMC data sets.

In line with our previous study, however, analysis of the intra-subjects standard deviations in both groups confirmed Bayes' law (Ernst & Banks, 2002), namely that merging multiple sensory cues such as visual and kinesthetic information for GREL estimates reduced the perceptual variability with respect to that measured when a single sensory channel (i.e., visual) is used (Fig. 4).

Interestingly, no relationship was found between the amount of body sway and the strength of the body tilt effect upon GREL estimates performed by arm movements (GREL-VP, Fig. 4B), in contrast to the significant correlation with GREL settings performed with vision alone (GREL-V, Fig. 4A). This might suggest that the experimental condition could nevertheless influence GREL perception among patients differently; the better compensated LDS (i.e., with lower body sway) showed a decreased GREL slope, whereas the less compensated showed an increased

GREL slope, when using the arm. Hence, only the former might have access to graviceptive cues from arm movement to counteract the body tilt effect in their GREL perception. Further results need to be obtained to validate this hypothesis, since our mean results showed no effect of the experimental condition across groups.

In conclusion, the present study demonstrates that the perception of the gravity-referenced eye level is not drastically affected in patients with long standing vestibular loss. Other sensory inputs such as somatosensory cues appear sufficient to provide as much information about gravity as the vestibular system for elaborating the geocentric component required in GREL judgements. This graviceptive information – in addition to that potentially arising from arm lifting movements (Gentaz & Hatwell, 1996) – cannot completely counterbalance the "body tilt effect" reported for both normals and LDS when judging the "Earth horizon". Nevertheless, our results illustrate the capability of patients with vestibular defect to correctly use alternative sensory information such as somatosensory cues in spatial judgement tasks.

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