Short and long-term postural learning to withstand galvanic vestibular perturbations.

Tjernström, Fredrik; Bagheri, Ali; Fransson, Per-Anders; Magnusson, Måns

Published in:
Journal of Vestibular Research: Equilibrium and Orientation

DOI:
10.3233/VES-2010-0391

2010

Citation for published version (APA):
Tjernström, F., Bagheri, A., Fransson, P.-A., & Magnusson, M. (2010). Short and long-term postural learning to withstand galvanic vestibular perturbations. *Journal of Vestibular Research: Equilibrium and Orientation*, *20*(6), 407-417. https://doi.org/10.3233/VES-2010-0391

Total number of authors:
4

Journal of Vestibular Research 20 (2010) 407–417
DOI 10.3233/VES-2010-0391
IOS Press

Short and long-term postural learning to withstand galvanic vestibular perturbations

Fredrik Tjernström*, Ali Bagher, Per-Anders Fransson and Måns Magnusson
Department of Otorhinolaryngology, Head and Neck Surgery, Clinical Sciences, Lund University Hospital, Lund, Sweden

Received 20 January 2010
Accepted 24 October 2010

Abstract. We investigated changes of postural responses to repeated bipolar galvanic vestibular stimulation on 5 consecutive days and once again after 3 months. Subjects consisted of 21 healthy volunteers. Except for the first day did the induced torque variance in response to galvanic vestibular stimulation not decrease within each test session, but there was a major reduction from day to day ($p < 0.001$) reflecting a continued processing of the postural experience gained during the stimulation. The decreased end level magnitude of postural responses after 5 days was retained after 3 months. The galvanic stimulation failed to induce larger torque variance compared to quiet stance toward the end of the 5 days as well as after 3 months, indicating a down-regulation of a repeated erroneous vestibular stimulation by the postural control system – i.e. sensory reweighting.

This argues that a major adaptation effect to galvanic vestibular perturbation takes place after the exposure to the stimulation – similar to the concept of the consolidation process involved in motor learning. This should be considered when repeatedly assessing vestibular function both clinically and in studies. It implies that sensory training involved in rehabilitation from vestibular diseases/deficiencies should be executed with spaced intervals in order to procure more efficient learning processes and in the end, a better function.

Keywords: Posture, adaptation, galvanic stimulation, memory

1. Introduction

The ability of the postural control system to adapt to changing constraints, formulate postural strategies and maintain the acquired abilities for later execution, is vital for the development of postural skills, as well as for the rehabilitation from any postural disturbance. Although the general treatment for postural difficulties and sensory loss constitutes of training exercises, the scientific basis is for this scarce and circumstantial. How often and long and with what intervals should postural rehabilitation training ideally be performed, are issues that need to be investigated.

Each of the sensory components of the postural control system can individually initiate a postural perturbation on application of external stimuli, which results in increased body-sway [1], e.g. the application of galvanic vestibular stimulation [2,3]. The net sum of bipolar galvanic stimulation (used in the present study) on stance signals a roll with a small yaw component towards the cathodal electrode [2]. This causes a change of postural sway towards the anodal side, laterally (right-left) sway when the head is facing forward [4, 5], and in the anteroposterior direction if the head is turned in the yaw-plane 90 degrees to either side [5,6]. Frequency analyses of induced body movements in response to galvanic stimulation have revealed that rapid (> 0.1 Hz) corrective postural movements are the most coherent with the effect of the galvanic stimulation [7] and that visual cues reduce evoked body movements $>$ 0.1 Hz [7–9] which is important to consider in order to correctly identify the effects of galvanic vestibular stimulation.

---

*Corresponding author: Fredrik Tjernström, Department of Otorhinolaryngology, Head and Neck Surgery, Clinical Sciences, Lund University Hospital, S-221 85 Lund, Sweden. Tel.: +46 4617 5849; Fax: +46 4621 10968; E-mail: Fredrik.Tjernstrom@med.lu.se.

ISSN 0957-4271/10/$27.50

Postural control is maintained by both feedback [10] and feed-forward [11] mechanisms. Feedback control depends on sensory input (vision, vestibular and somatosensation) that are processed, integrated and weighted to their relative importance and context in the central nervous system (CNS) [12–14]. Feed-forward mechanisms involve the concept of "internal models", whose output consists of preformed neuromuscular strategies that are activated in given situations, automatically or voluntarily (anticipated movements) or both in concert, according to previous postural experience. The dynamics of learning in postural control can be studied by investigating how induced postural sway changes over time. If the stimulation is applied for a long enough time-period, the induced responses diminish [1]. This reflects an adaptive process possibly due to a change of the relative impact or weighting that the affected sensory system has on the postural control system [12,15]. For example, when subjecting healthy subjects to a somatosensory perturbation repeatedly once a day during 5 consecutive days, the induced balance responses diminish during each test-session performed on each day but also from day to day [9,16]. This illustrates adaptation of postural responses when repeatedly exposed to the stimulus. These fast and more slow learning processes mimic how motor memories generally are formed; through consolidation of short-lasting into longer-lasting memories [17]. The concept of a consolidation process in motor memory formation is that the learnt skill is processed and modified by the appropriate neural structures, while not executing the skill itself [17]. Sleep is generally regarded as beneficial to the consolidation processes [18], and specifically during slow-wave sleep has it been shown that neuronal activities from preceding experience (or learning) are re-expressed in the hippocampus [19].

Adaptation of postural sway elicited by galvanic vestibular stimulation has been demonstrated in short-term perspective [7,20] to exhibit similar properties as responses to somatosensory adaptation [1]. Adaptation in a long-term perspective to repeated (5 times) mono-polar galvanic stimulation has been studied with the conclusion that most of the adaptation comes from being exposed to the stimulation the first time and there were no changes after the 2nd galvanic test [21].

In the present study we aimed to assess the importance of vestibular system on the process of postural short and long-term responses when the vestibular system was stimulated with repeated pulsatile bipolar galvanic stimulation initiating anteroposterior or lateral sway and the latter also with visual feedback, i.e. 3 conditions; head turned in yaw-plane 90 degrees with eyes closed and with the head facing forward eyes closed and open.

2. Material and methods

Galvanic vestibular stimulation was performed on 24 healthy volunteers. 1 subject (male) discontinued the trials on the cause of severe malaise, and 2 further subjects (both males) were excluded due to discomfort from the GVS. The age distribution of the remaining 21 subjects (8 male, 13 female) ranged from 17 to 41, mean 29 years. None of the subjects had previous experience of the experimental set up. None had any history of vertigo or central nervous disease, nor were on any form of medication, nor had consumed alcoholic beverages within 24 hours of any of the test occasions. The experiments were approved by the local ethical committee at Lund University Hospital and performed in accordance with the Helsinki Declaration of 1975.

2.1. Methods

The postural sway was recorded using a custom-made force-platform, developed at the Department of Solid Mechanics, Lund Institute of Technology, measuring the forces and torques actuated by the feet with 6 degrees of freedom. The data was sampled at 50 Hz by a computer equipped with an AD converter. The galvanic stimulation was applied on the mastoid processes through plates (3.5 × 4.5 cm) of carbon-based rubber glued in place with conductive glue. The electrical signal was alternating bipolar between ± 1 mA. The stimulation of galvanic vestibular stimulation was executed according to a computer controlled pseudo-random binary sequence (PRBS) schedule [22] of alternating bipolar galvanic stimulation for 200 seconds. The PRBS schedule composed of stimulation shift periods with random duration between 0.8–6.4 seconds, which yielded an effective bandwidth of the test stimulus in the region of 0.1–2.5 Hz. Thus, the designated square waved PRBS stimuli covered a broad power spectrum and the randomized stimulation reduced the opportunity to make anticipative and pre-emptive adjustments [1].

2.2. Procedure

Tests were conducted on 5 consecutive days and once again approximately 3 months later. During tests were subjects instructed to stand erect on the platform but not at attention, with their arms crossed over the chest and feet at an angle of about 30 degrees open to the front and heels 3 cm apart. Each test consisted of 2 conditions ‘Head forward-eyes closed’ and ‘Head forward-eyes open’, the order of visual condition was randomized and maintained on the consecutive test-days. For 12 of the subjects each test held an additional condition; ’Head turned-eyes closed’ (active head positioning approximately 90 degrees (yaw-plane) to preferred side [6]). The ‘Head turned-eyes closed’ condition was performed last on all days.

With eyes open the subjects fixated on a mark on the wall 1.5 m away. Each test in each condition lasted for 230 seconds, an initial 30 seconds of quiet stance and then 200 seconds of stimulation.

2.3. Data analysis

Torque variance was analyzed in the plane where the stimulus was most dominant, i.e. lateral (right-left) direction when the head was facing forward and the anteroposterior direction when the head was turned to the side [5,6]. In the data analysis, the variance of body sway was divided into three categories, viz. total, low frequency (< 0.10 Hz), and high frequency (> 0.10 Hz. A fifth-order digital Finite duration Impulse Response (FIR) filter [23], with filter components selected to avoid aliasing was used for spectral separation. The frequency cut-off level of 0.1 Hz was based on Fast Fourier Transformation (FFT) analysis of the sway composition under eyes closed and eyes open conditions [24]. The frequency limit at 0.1 Hz was also based upon empirical tests on recorded body sway, which have shown that this frequency limit is efficient when separating between fast corrective movements to maintain balance, and the smooth corrective changes in the overall stance. Regression analysis of the torque variance showed dependence to the test subjects’ squared weight and height, so the data were therefore normalized by squared weight and squared height.

Postural stability while standing is commonly analyzed using force platforms and the movements of the centre of pressure (CoP), i.e., the point of application of the ground reaction force. We measured torque and analyzed the variance of the torque values. Torque correspond to Centre of Pressure (CoP); torque τ is calculated from the formula $\tau = \mathrm{CoP} \cdot \mathrm{Fz}$; where $\mathrm{Fz} \approx \mathrm{m} \cdot \mathrm{g}$; where m = the assessed subjects mass (in kg) and g = gravitational constant 9.81 (in meter/s^2). Hence, changes in recorded torque are equivalent to changes in CoP [25]. The formula for variance is given by;

$$\bar{\tau} = \sum_{i=1}^{n} \frac{\tau(i)}{n}$$

$$var\tau = \frac{1}{n-1} \sum_{i=1}^{n} (\tau(i) - \bar{\tau})^2$$

i = sample, n = number of samples recorded during an analyzed period.

One benefit with presenting torque variance values is that the calculated value corresponds directly with the energy used towards the support surface to maintain stability [26].

Values were obtained for five periods during the test: the quiet stance period (0–30 seconds) before stimulation was applied, and from four periods (I–IV) during the stimulation (30–80, 80–130, 130–180, and 180–230 seconds, respectively). The effects of period, day, vision, and their interactions on recorded data were analyzed using a GLM univariate ANOVA (General Linear Model univariate Analysis of Variance) [27] test on log-transformed values. The accuracy of the GLM model was evaluated by testing whether the GLM model residuals provided by the statistical software (SPSS ver 17), were distributed normally. Analyses showed that normal GLM model residuals were better ensured if the torque variance data analysed by GLM model data was log-transformed prior to the analysis. This procedure was subsequently used in all GLM analyses.

In the GLM analysis, p-values < 0.05 were considered statistically significant. Since GLM analyses presume linear correlations, and adaptation could be nonlinear, we also applied post-hoc non-parametric analyses. Wilcoxon non-parametric test [27] was used for 4 comparisons; on each day between quiet stance and stimulation period I, between period 1 and 2, and period 1 and 4. Also period 1 and 4 across day 1, 5 and after 3 months was compared according to Wilcoxon. Non-parametric statistics were used since the obtained values were not normally distributed even after logarithmic transformation. P-values less than 0.013 were considered statistically significant in the Wilcoxon analysis, corrected according to the Bonferroni factor [27].

3. Results

3.1. Induced anteroposterior sway ‘head turned-eyes closed’

Torque variance values for this condition are presented in Fig. 2.

The galvanic perturbation resulted in an increased torque variance on almost all days in total and high frequency range, except for the 2nd and 4th day total and 3rd day high frequency (Fig. 2). The galvanic perturbation did not induce increased sway in low frequency range until the 5th day ($p = 0.007$), and also after 3 months ($p = 0.009$) (Fig. 2).

According to the GLM ANOVA analysis (Table 1) were there no significant differences of induced torque variance between the periods (during the test) at any frequency, however post-hoc analysis demonstrated a significant reduction of induced torque variance between 1st period and 2nd on the 1st day total torque variance (0.003), and on the 1st and 2nd day high frequency range (Fig. 2). There were also significant reductions between the 1st and 4th period on the 2nd day in total and high frequency range (Fig. 2). No differences in the amount of induced torque variance could be discerned in low frequency range.

According to GLM ANOVA Analysis was there significant reduction of torque variance from day to day in the high frequency range ($p < 0.001$), but not in total or low frequency range (Table 1). Post-hoc Wilcoxon analysis demonstrated significant reductions of induced torque variance between the 1st and 5th day in high frequency range (period 1 $p = 0.002$ and period 3 $p = 0.007$) (Fig. 2). There were no statistical significant differences in total and low frequency range between day 1 and 5.

There were no statistical significant differences in any frequency range of induced torque variance between the 5th and 90th day.

3.2. Induced lateral sway ‘head forward-eyes closed’

Torque variance values for this condition are presented in Fig. 3.

The galvanic perturbation resulted in increased torque variance in total and low frequency range on the 1st and 4th day, and in high frequency range on the 1st day (Fig. 3).

According to the GLM ANOVA analysis (Table 1) were there no significant differences of induced torque variance between the periods (during the test) at any frequency, however post-hoc analysis demonstrated a significant reduction of induced torque variance between the 1st period and 2nd period ($p < 0.001$) and between the 1st and 4th period ($p = 0.008$) in total range on the 1st day (Fig. 3). No significant reductions of torque variance were found on any other day or frequency range.

According to GLM ANOVA Analysis (Table 1) there was significant reduction of torque variance from day to day in total and high frequency range ($p < 0.001$). Post-hoc Wilcoxon analysis demonstrated significant reductions of induced torque variance between the 1st and 5th day as is depicted in Fig. 3, predominantly in total and high frequency range (Fig. 3).

There was an increase in torque variance between the 5th and 90th day period 2 ($p = 0.006$) (Fig. 3).

3.3. Induced lateral sway ‘head forward-eyes open’

Torque variance values for this condition are presented in Fig. 4.

The galvanic perturbation resulted in increased torque variance in total and high frequency range on the 1st and 2nd day. The galvanic perturbation did not induce increased sway in low frequency range on any day (Fig. 4).

According to the GLM ANOVA analysis (Table 1) were there no significant differences of induced torque variance between the periods (during the test) at any frequency, however post-hoc analysis demonstrated a significant increase of total torque variance between the 1st and 4th period on the 5th day (Fig. 4). No significant difference of torque variance could be demonstrated between the 1st and 2nd period any day or frequency range.

According to GLM ANOVA Analysis was there significant reduction of torque variance from day to day in total and high frequency range ($p < 0.001$) (Table 1). Post-hoc Wilcoxon analysis demonstrated significant reductions of induced torque variance between the 1st and 5th day as is depicted in Fig. 4, in total and high frequency range (Fig. 4).

There were no statistical significant differences in any frequency range of induced torque variance between the 5th and 90th day.

3.4. Effect of visual cues

The induced torque variance differed between the visual conditions in low frequency range (Figs 1 and 2) with higher amplitudes with eyes open than closed ($p < 0.05$). This is not obvious from the figures but becomes apparent when examining the individual data. The effect of vision on the level of induced torque variance in total and high frequency range could not be distinguished in the GLM ANOVA analysis (Table 2). No interactions between vision and the variables ‘Day’ and ‘Period’ could be found with GLM ANOVA.

Table 1
Adaptation to galvanic vestibular stimulation according to ANOVA

Test condition	Frequency range	Period	Day	Period/Day
'Head turned-eyes closed'	**Total**	ns	ns	ns
	< 0.1 Hz	ns	ns	ns
	> 0.1 Hz	ns	**< 0.001**	ns
'Head forward – eyes closed'	**Total**	ns	**< 0.001**	ns
	< 0.1 Hz	ns	ns	ns
	> 0.1 Hz	ns	**< 0.001**	ns
'Head forward-eyes open'	**Total**	ns	**< 0.001**	ns
	< 0.1 Hz	ns	ns	ns
	> 0.1 Hz	ns	**< 0.001**	ns

Effects of the consecutive period (Period), consecutive day (Day), and their interactions on recorded lateral torque variance analyzed using a GLM univariate ANOVA (General Linear Model univariate Analysis of Variance) test on log-transformed values.

Table 2
Vision and Adaptation according to ANOVA

Frequency range	Period	Day	Vision	Period/Day	Period/Vision	Day/Vision	Period/Day/Vision
Total	ns	< 0.001	ns	ns	ns	ns	ns
< 0.1 Hz	ns	ns	ns	ns	ns	ns	ns
> 0.1 Hz	ns	< 0.001	0,025	ns	ns	ns	ns

This table only refer to data presented in Figs 3 and 4 (i.e. head forward eyes closed/open). Effects of the consecutive period (Period), consecutive day (Day), vision (Eyes closed, Eyes open), and their interactions on recorded lateral torque variance analyzed using a GLM univariate ANOVA (General Linear Model univariate Analysis of Variance) test on log-transformed values.

4. Discussion

4.1. Short-term adaptation

Most of the adaptation of induced responses in 'Head forward' condition both visual conditions seemed to occur already at the 1st day between the 1st and subsequent periods. In the further tests the seeming lack of a decrease of torque values during a test was surprising, as it contrasts to previous studies on adaptation to GVS [7,20]. Subjects tended to increase the induced torque variance toward the end of each test in all 3 conditions, which possibly could be ascribed fatigue due to our protocol with long stimulation periods (200s). It is possible that shorter test-protocols would yield significant short-term reductions of induced torque variance for all test conditions. It should be noted however that somatosensory perturbation of subjects of the same duration does not yield any distinguishable fatiguing effects [9], and it is rare that healthy subjects discontinue the trials due to discomfort when the somatosensory system is perturbed. It seems as if galvanic vestibular stimulation induces more discomfort than somatosensory stimulation, although the latter induces more movement, up to 10 times the level of torque variance.

Galvanic vestibular stimulation induce a sensory mismatch between vestibular and visual cues [28] and perhaps also otolith canal mismatch [29]. This was evident for our series where 3 subjects had to discontinue the tests of such symptoms. Motion sickness is well known to reduce alertness also when there are no overt symptoms [30]. Reduced alertness may per se affect postural control as may the sensory mismatch [25]. This may explain an increased sway at the end of the long stimulation periods and hence either conceal or reverse any adaptation.

Bipedal stance is more stable in the lateral than in the anteroposterior plane which could account for the apparent stability of induced torque during each test. However the head turned condition, which ensured greater torque values through anteroposterior body sway, displayed also hardly any decreases of induced torque between the periods during each test.

4.2. Long-term adaptation

The decrease of total and high frequency torque variance in 'Head forward' both visual conditions were highly significant between the tests, signifying a learning from the experience the previous day, whether the acquired ability constitutes of a disregard to misleading stimulus or a continuing adjustment of postural movements in response to the perturbing stimulus [9]. The decrease were the same whether visual cues were available or not and most prominent in the high frequency

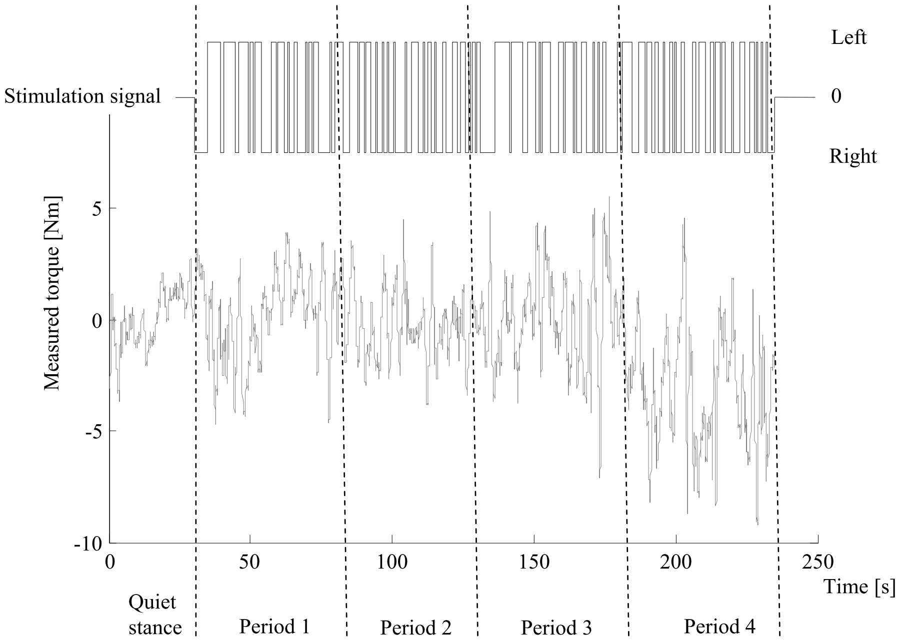

Fig. 1. Division of each test into quiet stance and periods of perturbation (1–4).

range, consistent with the known effect of the stimulus on body movements [7]. Although the galvanic perturbation yielded hardly any increase of torque variance compared to quiet stance (‘Head forward’ conditions) were the body adjustments adjusted and reduced from day to day basis. It is not probable that this is an effect that can be attributed to just standing on the force-platform since quiet stance values did not vary significantly in any frequency range between the days, which is in accordance with previous studies with repeated posturography measurements [9,31].

In the ‘Head turned-eyes closed’ condition could significant reduction of induced torque variance only be demonstrated in high frequency range but not in the total (Table 1). This appears to be due to a concomitant increase in low frequency movements although not reaching statistical significance. Galvanic stimulation did not induce higher torque than quiet stance in the low frequency range until the 5th day (Fig. 2). This is an interesting finding since it suggests that the postural strategy to withstand galvanic vestibular perturbation shifts from fast corrective movements to slow alterations of stance.

Balter et al. [21] analyzed adaptation to mono-polar galvanic stimulation on several test-occasions with different time-intervals and concluded that there were only differences in the results between the first and second test-occasion irrespective of interval. Also in the present study a large part of torque reduction takes place between the first two test-occasions, however the reduction between the 1st and 2nd day would not suffice to yield significant values to the ‘day’ variable in the GLM ANOVA analysis, and the Figs 1–3 show a continuing reduction of torque variance from day to day in the high frequency range. The effects of the galvanic stimulation on torque compared to quiet stance decreased from the first day onwards to reach non-significant levels on day 3-4 for condition eyes closed and open, suggesting that the stimulation was insufficient to yield even a postural disturbance toward the end of the 5 days. This must be considered if the method of GVS is used to repeatedly evaluate the patency of patients’ vestibular system.

4.3. Retrieval after 3 months

The ability to respond to galvanic stimulation with low torque variance levels was preserved over 3 months in the high frequency range in all 3 conditions (Figs 2–4). The postural responses in the total frequency range seem also to be well retrieved in ‘Head forward’ both visual conditions but not in ‘Head turned-eyes closed’. ‘Head turned-eyes closed’ seemed to induce an increase of low frequency movements over the days,

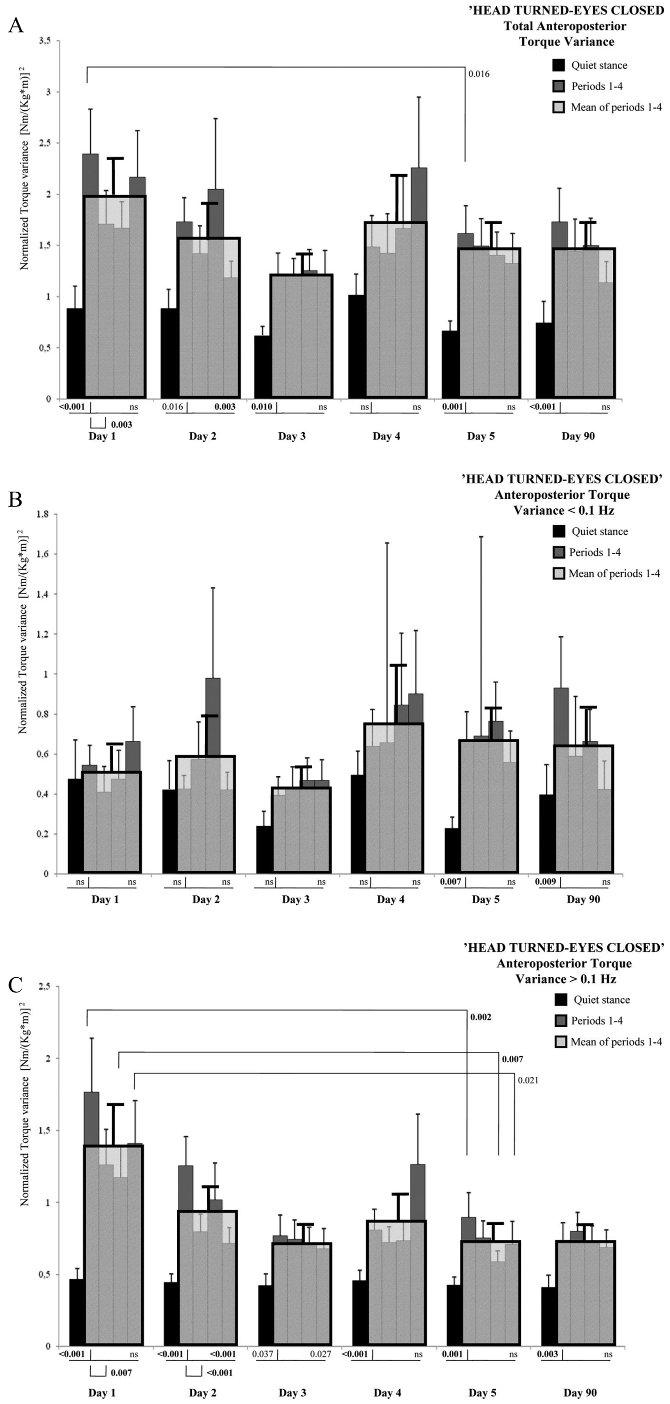

Fig. 2. Mean and standard error of mean (SEM) of elicited torque in anteroposterior direction for 'Head turned-eyes closed', for total, low and high frequency range. Black bars indicate the quiet stance periods (0–30 s). Dark grey bars indicate the individual periods of galvanic stimulation I–IV (30–80, 80–130, 130–180, and 180–230 s). Light transparent grey bars indicate the mean of all the periods of stimulation on each day. Please note the higher level of torque variance compared to that demonstrated in Figs 3 and 4. The annotation above the graphs shows the statistical comparison between the periods of galvanic stimulation between day 1 and 5, and day 5 and 90. Significant values are shown in bold, but also those that fell out due to Bonferroni correction. The annotation below the graphs statistics shows the statistical comparison between the period of quiet stance and galvanic period 1, between galvanic period 1 and 2, and between period 1 and 4 Significant values according to Bonferroni are in bold.

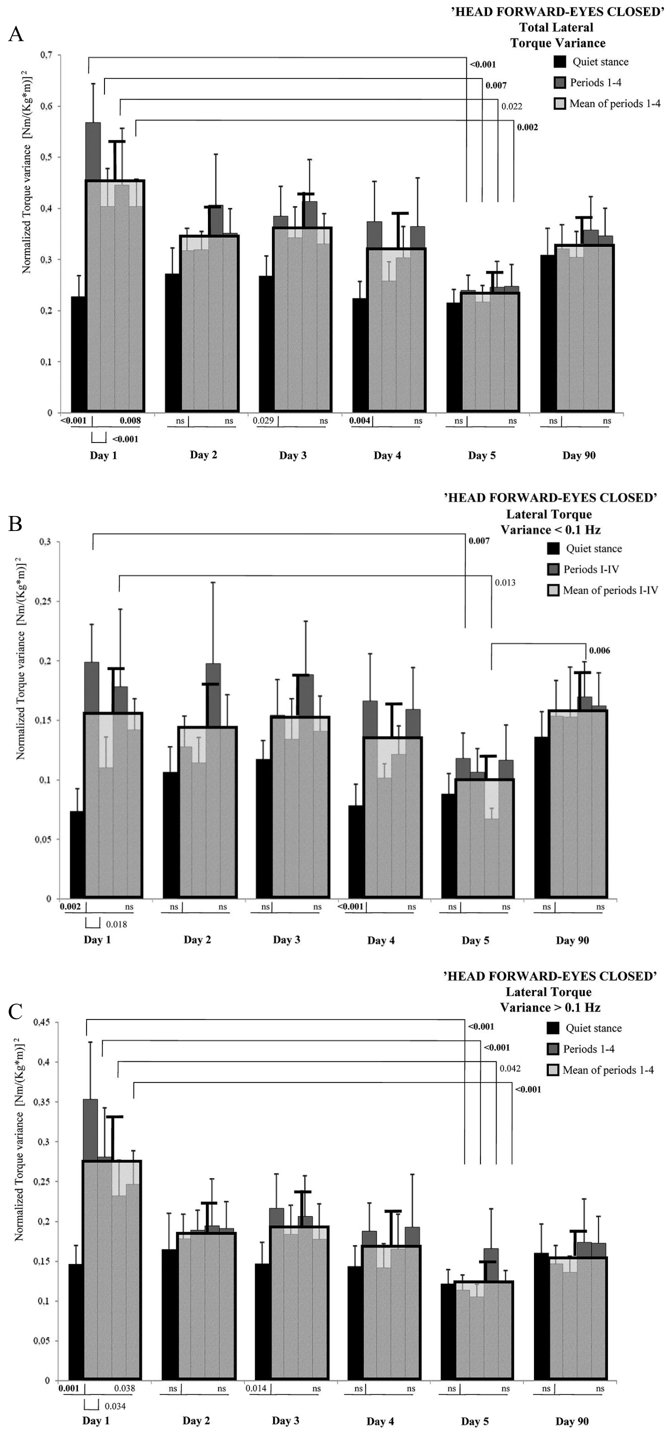

Fig. 3. Mean and standard error of mean (SEM) of elicited torque in lateral direction during 'Head forward-eyes closed', for total, low and high frequency range. Black bars indicate the quiet stance periods (0–30 s). Dark grey bars indicate the individual periods of galvanic stimulation 1–4 (30–80, 80–130, 130–180, and 180–230 s). Light transparent grey bars indicate the mean of all the periods of stimulation on each day. The annotation above the graphs shows the statistical comparison between the periods of galvanic stimulation between day 1 and 5, and day 5 and 90. Significant values are shown in bold, but also those that fell out due to Bonferroni correction. The annotation below the graphs statistics shows the statistical comparison between the period of quiet stance and galvanic period 1, between galvanic period 1 and 2, and between period 1 and 4 Significant values according to Bonferroni are in bold.

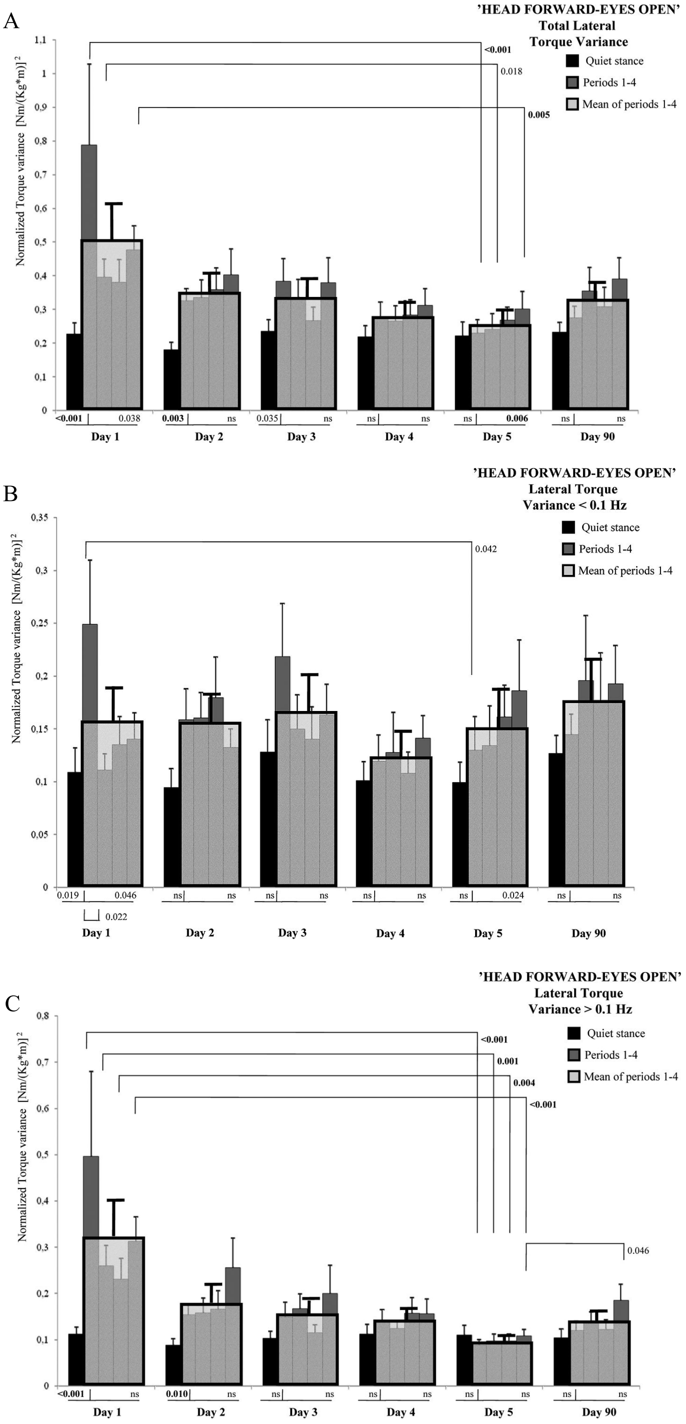

Fig. 4. Mean and standard error of mean (SEM) of elicited torque in lateral direction 'Head forward-eyes open', for total, low and high frequency range. Black bars indicate the quiet stance periods (0–30 s). Dark grey bars indicate the individual periods of galvanic stimulation I–IV (30–80, 80–130, 130–180, and 180–230 s). Light transparent grey bars indicate the mean of all the periods of stimulation on each day. The annotation above the graphs shows the statistical comparison between the periods of galvanic stimulation between day 1 and 5, and day 5 and 90. Significant values are shown in bold, but also those that fell out due to Bonferroni correction. The annotation below the graphs statistics shows the statistical comparison between the period of quiet stance and galvanic period 1, between galvanic period 1 and 2, and between period 1 and 4 Significant values according to Bonferroni are in bold.

which would explain some of the total torque values and the 'low frequency strategy' was also interestingly preserved over 3 months as the stimulation yielded increased torque compared to quiet stance.

The results suggest that short-term adaptation in this stimulation-protocol is limited. It seems as if the responses to galvanic perturbation after a short time of stimulation (1st period 1st day) reach a level where further exposure is of no or little benefit to enhance the ability to withstand the perturbation. Furthermore, it seems as if the experience from the stimulation is advantageous when exposed to the stimulation at another time (in our case days).This argues that there is an adaptation effect to galvanic vestibular perturbation that takes place after the exposure – similar to the concept of the consolidation process involved in motor learning [32]. The process of consolidation to responses to galvanic vestibular stimulation seemed to be strong enough to preserve the responses at least up to 3 months, thus indicating formation of long-term memory.

It is interesting to note that the postural adaptation to a vestibular perturbation differ compared to the adaptation to somatosensory perturbations, in which there are both short and long-term adaptive processes [9]. It is unclear why the adaptation should differ since they both carry a necessity for the postural control system to adapt. One may speculate that vestibular information is of such importance, from an evolutionary perspective, that no further depression is allowed, and that we only see the first part of the adaptive process, which might be an immediate sensory reweighting.

It is also of interest that galvanic stimulation induced a change of postural strategy in 'Head turned-eyes closed' condition. Although the torque variance differences were not significant in low frequency, the data certainly suggest a change from decreasing high to increasing low frequency movements as the test progressed through the days, i.e. a new postural strategy. This indicates that the process of adaptation to galvanic vestibular stimulation does indeed correspond to a continuing adjustment of postural movements in response to the perturbing stimulus and not only in resolving a sensory conflict. The same postural strategy appeared to be present after 3 months, which suggests that the strategy consists of a consolidated changed response to galvanic vestibular stimulation and as such constituting an internal model used in feed-forward control postural responses.

The fact that galvanic stimulation failed to induce higher torque levels toward the end of the 5 days as well as after 3 months in 'Head forward' both visual conditions, indicate that by repeating the vestibular stimulation it becomes ignored by the postural control system – a sensory reweighting. The concept of sensory reweighting is widely accepted although rarely demonstrated experimentally.

The results suggest that the consolidation process of responses to vestibular perturbations is most effective and this should be considered when assessing vestibular function repeatedly in the lateral plane, as well as when designing studies involving repeated galvanic vestibular stimulation. It may be further suggested that sensory training involved in rehabilitation from vestibular diseases/deficiencies should be executed with spaced intervals rather than mass-training in order to procure more efficient learning processes [33,34].

References

[1] P.A. Fransson, A. Hafstrom, M. Karlberg, M. Magnusson, A. Tjader and R. Johansson, Postural control adaptation during galvanic vestibular and vibratory proprioceptive stimulation, *IEEE Trans Biomed Eng* **50**(12) (2003), 1310–1319.

[2] R.C. Fitzpatrick and B.L. Day, Probing the human vestibular system with galvanic stimulation, *J Appl Physiol* **96**(6) (2004), 2301–2316.

[3] H.G. MacDougall, S.T. Moore, I.S. Curthoys and F.O. Black, Modeling postural instability with Galvanic vestibular stimulation, *Exp Brain Res* **172**(2) (2006), 208–220.

[4] A.E. Pavlik, J.T. Inglis, M. Lauk, L. Oddsson and J.J. Collins, The effects of stochastic galvanic vestibular stimulation on human postural sway, *Exp Brain Res* **124**(3) (1999), 273–280.

[5] S. Lund and C. Broberg, Effects of different head positions on postural sway in man induced by a reproducible vestibular error signal, *Acta Physiol Scand* **117**(2) (1983), 307–309.

[6] P.A. Fransson, M. Karlberg, T. Sterner and M. Magnusson, Direction of galvanically-induced vestibulo-postural responses during active and passive neck torsion, *Acta Otolaryngol* **120**(4) (2000), 500–503.

[7] R. Johansson, M. Magnusson and P.A. Fransson, Galvanic vestibular stimulation for analysis of postural adaptation and stability, *IEEE Trans Biomed Eng* **42**(3) (1995), 282–292.

[8] B.L. Day, M. Guerraz and J. Cole, Sensory interactions for human balance control revealed by galvanic vestibular stimulation, *Adv Exp Med Biol* **508** (2002), 129–137.

[9] F. Tjernstrom, P.A. Fransson, A. Hafstrom and M. Magnusson, Adaptation of postural control to perturbations – a process that initiates long-term motor memory, *Gait Posture* **15**(1) (2002), 75–82.

[10] R. Johansson, M. Magnusson and M. Akesson, Identification of human postural dynamics, *IEEE Trans Biomed Eng* **35**(10) (1988), 858–869.

[11] D.M. Wolpert, Z. Ghahramani and M.I. Jordan, An internal model for sensorimotor integration, *Science* **269**(5232) (1995), 1880–1882.

[12] R.J. Peterka, Sensorimotor integration in human postural control, *J Neurophysiol* **88**(3) (2002), 1097–1118.

[13] N. Vuillerme and N. Pinsault, Re-weighting of somatosensory inputs from the foot and the ankle for controlling posture during quiet standing following trunk extensor muscles fatigue, *Exp Brain Res* **183**(3) (2007), 323–327.

[14] J.J. Jeka, K.S. Oie and T. Kiemel, Asymmetric adaptation with functional advantage in human sensorimotor control, *Exp Brain Res* **191**(4) (2008), 453–463.

[15] K.S. Oie, T. Kiemel and J.J. Jeka, Multisensory fusion: simultaneous re-weighting of vision and touch for the control of human posture, *Brain Res Cogn Brain Res* **14**(1) (2002), 164–176.

[16] P.A. Fransson, R. Johansson, F. Tjernstrom and M. Magnusson, Adaptation to vibratory perturbations in postural control, *IEEE Eng Med Biol Mag* **22**(2) (2003), 53–57.

[17] R. Shadmehr and T. Brashers-Krug, Functional stages in the formation of human long-term motor memory, *J Neurosci* **17**(1) (1997), 409–419.

[18] B. Shen and B.L. McNaughton, Modeling the spontaneous reactivation of experience-specific hippocampal cell assembles during sleep, *Hippocampus* **6**(6) (1996), 685–692.

[19] M.A. Wilson and B.L. McNaughton, Reactivation of hippocampal ensemble memories during sleep, *Science* **265**(5172) (1994), 676–679.

[20] S.G. Balter, R.J. Stokroos, E. Akkermans and H. Kingma, Habituation to galvanic vestibular stimulation for analysis of postural control abilities in gymnasts, *Neurosci Lett* **366**(1) (2004), 71–75.

[21] S.G. Balter, R.J. Stokroos, R.M. Eterman, S.A. Paredis, J. Orbons and H. Kingma, Habituation to galvanic vestibular stimulation, *Acta Otolaryngol* **124**(8) (2004), 941–945.

[22] R. Johansson, System Modeling and Identification, *Prentice Hall Englewood Cliffs*, NJ, 1993.

[23] J.G.M.D. Proakis, *Introduction to Digital Signal Processing*, New York: Macmillan, 1989.

[24] H. Petersen, M. Magnusson, P.A. Fransson and R. Johansson, Vestibular disturbance at frequencies above 1 Hz affects human postural control, *Acta Otolaryngol* **114**(3) (1994), 225–230.

[25] M. Patel, S. Gomez, S. Berg, P. Almbladh, J. Lindblad, H. Petersen, M. Magnusson, R. Johansson and P.A. Fransson, Effects of 24-h and 36-h sleep deprivation on human postural control and adaptation, *Exp Brain Res* **185**(2) (2008), 165–173.

[26] M. Magnusson, R. Johansson and J. Wiklund, Galvanically induced body sway in the anterior-posterior plane, *Acta Otolaryngol* **110**(1–2) (1990), 11–17.

[27] D. Altman, *Practical Statistics for Medical Research*, New York: Chapman & Hall NY, 1991.

[28] A. Bronstein, Visual symptoms and vertigo, *Neurol Clin* **23**(3) (2005), 705–713, v–vi.

[29] M. Karlberg, L. McGarvie, M. Magnusson, S.T. Aw and G.M. Halmagyi, The effects of galvanic stimulation on the human vestibulo-ocular reflex, *Neuroreport* **11**(17) (2000), 3897–3901.

[30] A. Graybiel and J. Knepton, Sopite syndrome: a sometimes sole manifestation of motion sickness, *Aviat Space Environ Med* **47**(8) (1976), 873–882.

[31] H. Ishizaki, I. Pyykko, H. Aalto and J. Starck, Repeatability and effect of instruction of body sway, *Acta Otolaryngol Suppl* **481** (1991), 589–592.

[32] J.L. McGaugh, Memory – a century of consolidation, *Science* **287**(5451) (2000), 248–251.

[33] P.A. Fransson, E.K. Kristinsdottir, A. Hafström, M. Magnusson and R. Johansson, Balance control and adaptation during vibratory perturbations in middle-aged and elderly humans, *Eur J Appl Physiol* **91**(5–6) (2004), 595–603.

[34] A.J. Campbell et al., Randomised controlled trial of a general practice programme of home based exercise to prevent falls in elderly women, *Bmj* **315**(7115) (1997), 1065–1069.