Neuroscience Letters 581 (2014) 75–79

Contents lists available at ScienceDirect

Neuroscience Letters

journal homepage: www.elsevier.com/locate/neulet

Verticality perception during and after galvanic vestibular stimulation

Katharina Volkening[a,b,c,*,1], Jeannine Bergmann[b,c,1], Ingo Keller[b,c], Max Wuehr[c], Friedemann Müller[b,c], Klaus Jahn[c,d]

[a] Graduate School of Systemic Neurosciences, Ludwig-Maximilians-University, Großhaderner Str. 2, 82152 Planegg-Martinsried, Germany
[b] Schoen Klinik Bad Aibling, Kolbermoorerstr. 72, 83043 Bad Aibling, Germany
[c] German Center for Vertigo and Balance Disorders (DSGZ), Ludwig-Maximilians-University, Marchioninistr. 15, 81377 Munich, Germany
[d] Department of Neurology, Ludwig-Maximilians-University, Marchioninistr. 15, 81377 Munich, Germany

HIGHLIGHTS

- GVS causes verticality deviations towards the anode during stimulation.
- After stimulation, the subjective verticals deviate towards the cathode.
- Aftereffects of GVS (1.5 mA, 20 min) exhibit different types of decay.
- GVS effects are best assessed with the subjective haptic vertical.

ARTICLE INFO

Article history:
Received 4 February 2014
Received in revised form 11 August 2014
Accepted 15 August 2014
Available online 23 August 2014

Keywords:
Galvanic vestibular stimulation
Subjective vertical
Verticality perception

ABSTRACT

The human brain constructs verticality perception by integrating vestibular, somatosensory, and visual information. Here we investigated whether galvanic vestibular stimulation (GVS) has an effect on verticality perception both during and after application, by assessing the subjective verticals (visual, haptic and postural) in healthy subjects at those times. During stimulation the subjective visual vertical and the subjective haptic vertical shifted towards the anode, whereas this shift was reversed towards the cathode in all modalities once stimulation was turned off. Overall, the effects were strongest for the haptic modality. Additional investigation of the time course of GVS-induced changes in the haptic vertical revealed that anodal shifts persisted for the entire 20-min stimulation interval in the majority of subjects. Aftereffects exhibited different types of decay, with a preponderance for an exponential decay. The existence of such reverse effects after stimulation could have implications for GVS-based therapy.

1. Introduction

Humans construct and update their sense of verticality by integrating vestibular, somatosensory, and visual input [18]. The internal estimate of verticality can be assessed by different methods, testing preferentially the visual, the tactile and the postural modalities (subjective visual, haptic, and postural vertical). These modalities can be differentially affected in patients with neurological disorders [4,23,33].

Transmastoidal galvanic vestibular stimulation (GVS) acts on afferents from the otoliths and the semicircular canals [8]. It was also shown to affect subjects' perception of verticality. During stimulation the subjective visual (SVV) and the subjective haptic vertical (SHV) deviate towards the anode [21,22,24]. GVS causes eye torsion and nystagmus via the vestibular-ocular reflex [13] and – with the head upright – body tilt towards the anode via vestibulo-spinal reflexes [31].

However, existing studies on verticality perception have only examined the online effects of GVS, since judgments of verticality were always generated *during* stimulation intervals. In the oculomotor domain, GVS is known though to elicit reverse responses towards the cathode *after* stimulation [20,26]. It is not known if these aftereffects exist for the subjective verticals and whether there are any differences between modalities. This is of relevance since the time course and magnitude of effects and aftereffects of GVS on verticality perception might influence responses to

* Corresponding author at: Schoen Klinik Bad Aibling, Kolbermoorer Str. 72, 83043 Bad Aibling, Germany. Tel.: +49 8061 903 1903.
E-mail addresses: volkening.kathi@googlemail.com (K. Volkening), JBergmann@schoen-kliniken.de (J. Bergmann), IKeller@schoen-kliniken.de (I. Keller), FMueller@schoen-kliniken.de (F. Müller), klaus.jahn@med.uni-muenchen.de (K. Jahn).
[1] Joint first authors.

http://dx.doi.org/10.1016/j.neulet.2014.08.028
0304-3940/

therapeutic interventions. Thus, the purpose of this study was to examine the influence of GVS on different subjective verticals (visual, haptic, and postural) both during and after its application.

2. Materials and methods

2.1. Galvanic vestibular stimulation

Bilateral bipolar GVS was delivered by a battery-driven, direct current stimulator (neuroConn Ilmenau, Germany). Electrodes were covered with natrium-chloride soaked sponges (30 cm^2 each). Current was ramped up (in steps of 0.1 mA/s) to 1.5 mA and turned off at the end of the stimulation period.

2.2. Assessment of verticality perception

2.2.1. Subjective visual vertical (SVV)
The SVV was assessed with the so-called bucket test. The bucket was rotated by the examiner, and the seated subjects indicated when they visually perceived a dark line (13 cm long, 0.3 cm wide, at 23 cm distance) as being vertical [35].

2.2.2. Subjective haptic vertical (SHV)
The SHV was measured with a rod (27 cm long, 1 cm wide) mounted onto a vertical plate 40 cm in front of the subject (see [10] for a similar device). While seated and blindfolded, the subjects' task was to adjust the wooden rod, with their right hand using a precision grip until they perceived it to be in a vertical position. They were not allowed to touch the device's plate or the desk.

2.2.3. Subjective postural vertical (SPV)
The SPV was measured in the Spacecurl [2], a cardanic suspension apparatus that consists of three concentric rings. The blindfolded subject stood in the centre of the apparatus on a platform that was attached to the midmost ring. The device was tilted in the frontal plane, and subjects had to indicate when they felt they were in an upright position.

There was no time limit for individual adjustments. Six adjustments per condition were performed in randomized order of starting positions (for SPV 12°, 15° & 18°; for SVV and SHV 15°, 25° & 40°). Half of the adjustments started from a clockwise, half from a counter-clockwise position. The six adjustments were averaged for each condition and modality to calculate the SPV, SVV, and SHV. Data were normalized so that positive values indicated deviations from the earth vertical to the side of the anode, and negative values, deviations in the direction of the cathode.

2.3. Experiments

The Ethics Committee of the Ludwig-Maximilians-University Munich approved this study. All subjects provided their written informed consent.

2.3.1. Exp. 1: Manipulation of subjective verticals
To investigate online effects and aftereffects of GVS on verticality perception across different modalities, ten healthy subjects participated in experiment 1 (mean age: 59 years, SD: ±6; 5 females).

All subjects performed the SPV, the SVV, and the SHV immediately before (baseline), during, and 3 min after a period of GVS. The experiment was conducted on two consecutive days with a fixed sequential order: the SPV on day 1, the SVV and SHV on day 2. The polarity of the GVS current was varied between subjects. Stimulation was applied for the duration of verticality adjustments (4–8 min).

2.3.2. Exp. 2: Time course
A second experiment was designed to determine the time course of online effects and aftereffects of GVS on verticality perception. Since the haptic modality was most responsive to GVS, the time course was studied for the SHV. Fourteen healthy subjects (mean age: 34 years, SD: ±6; 7 females), not included in experiment 1, were tested in experiment 2. The subjects repeatedly performed the SHV during and after a 20-min period of GVS. Six SHV adjustments were performed immediately before starting GVS (baseline), 0.5, 5, 10, 15, and 20 min after starting the stimulation (conditions 1–5) and at the same time points after terminating GVS (conditions 6–10) (total of 66 adjustments). All subjects were stimulated with the cathode over the left and the anode over the right mastoid.

2.4. Data analysis

A one-way ANOVA with the within-subject factor modality was used to evaluate differences between modalities at baseline. To determine any differences in verticality adjustments across time points (baseline, during, after GVS), and modalities (SVV, SHV, SPV) a factorial repeated-measures ANOVA was performed with two within-subject factors (time and modality). Another factorial repeated-measures ANOVA (within-subjects factors modality and type of effect) was conducted to compare the magnitudes of online effects and aftereffects across modalities. Effect magnitudes were calculated as absolute differences between baseline and during GVS (online effect) and during and after GVS (aftereffect). If sphericity was violated in an ANOVA, Greenhouse–Geisser correction was applied. In case of significant results subsequent multiple comparisons were performed and Bonferroni corrected.

For experiment 2 differences across conditions were analyzed using a one-way repeated-measures ANOVA and subsequent repeated contrasts. Verticality adjustments during (condition 1–5) and after GVS (condition 6–10) were grouped and compared using a paired *t*-test. A least-squares method was used to estimate which type of model (no decay, linear decay or exponential decay) best fits the individual time course of responses in verticality perception during and after GVS. A decay time constant was calculated for subjects showing an exponential decay. The data were analyzed with Matlab (The Mathworks, Version 2011b) and SPSS Statistics (SPSS Inc., Version 17.0). The significance level for α was set at 0.05.

3. Results

3.1. Exp. 1: Manipulation of subjective verticals

There was no significant difference between the modalities at baseline ($F(2,27) = 0.056$, $p = 0.945$; mean ± SE: SVV = 0.8 ± 0.5°, SHV = 0.6 ± 0.6°, SPV = 0.6 ± 0.4°). The factorial repeated-measures ANOVA across all time points, showed a significant main effect of time ($F(1.27,11.41) = 20.852$, $p < 0.001$), but not of modality ($F(2,18) = 2.082$, $p = 0.154$). Post hoc tests revealed significant differences between the adjustments before and during GVS ($p = 0.006$) and during and after GVS ($p < 0.001$), but not between baseline and after GVS ($p = 1.000$). There was a significant interaction between time and modality ($F(2.39,21.50) = 9.265$, $p = 0.001$): Differences between adjustments before and during GVS were smaller for the SPV than for the SVV and SHV; adjustments during and after GVS were also smaller for the SPV than for the SHV. Analysis of the effect magnitudes showed a significant main effect of modality ($F(2,18) = 17.260$, $p < 0.001$), but no effect of effect type (online effect vs. aftereffect) ($F(1,9) = 0.520$, $p = 0.489$) and no significant interaction ($F(1.16,10.42) = 1.506$, $p = 0.252$). Post hoc tests revealed significantly greater online effects and aftereffects for the SHV than