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Subliminal galvanic-vestibular stimulation recalibrates the distorted visual and tactile subjective vertical in right-sided stroke

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ABSTRACT

Stroke of the right cerebral hemisphere often causes deficits in the judgement of the subjective visual vertical (SVV) and subjective tactile vertical (STV) which are related to central vestibular functioning. Clinically, deficits in the SVV/STV are linked to balance problems and poor functional outcome. Galvanic Vestibular Stimulation (GVS) is a non-invasive, save stimulation technique that induces polarity-specific changes in the cortical vestibular systems. Subliminal GVS induces imperceptible vestibular stimulation without unpleasant side effects. Here, we applied bipolar subliminal GVS over the mastoids (mean intensity: 0.7 mA, 20 min duration per session) to investigate its online-influence on constant errors, difference thresholds and range values in the SVV and STV. 24 patients with subacute, single, unilateral right hemisphere stroke were studied and assigned to two patient groups (impaired vs. normal in the SVV and STV) on the basis of cut-off scores from healthy controls. Both groups performed these tasks under three experimental conditions on three different days: a) sham GVS where electric current was applied only for 30 s and then turned off, b) left-cathodal GVS and c) right-cathodal GVS, for a period of 20 min per session. Left-cathodal GVS, but not right-cathodal GVS significantly reduced all parameters in the SVV. Concerning STV GVS also reduced constant error and range numerically, though not significantly. These effects occurred selectively in the impaired patient group. In conclusion, we found that GVS rapidly influences poststroke verticality deficits in the visual and tactile modality, thus highlighting the importance of the vestibular system in the multimodal elaboration of the subjective vertical.

1. Introduction

The human brain constructs verticality perception by integrating vestibular, somatosensory and visual information. The correct perception of verticality is an important requirement for efficiently moving and acting in the world. An impairment of this ability frequently follows stroke as indicated by deviations of the patients' subjective visual vertical (SVV) larger than $\pm 2°$ from the earth vertical (Bender and Jung, 1948; Kerkhoff, 1999; Yelnik et al., 2002; Utz et al., 2011b). In this task patients have to judge when a rod, that is rotated mostly in the frontal (roll) plane, is aligned with the earth vertical. In addition to the visual domain, disturbed perception of verticality after stroke has been observed in the haptic modality. In the haptic variant of the task a rod has to be adepted with one hand (typically the nonparetic, ipsilesional hand) to the earth vertical (subjective tactile vertical = STV) while blindfolded. Tilts in these two sensory verticals are significantly associated with impairments in other perceptual tasks (i.e. line orientation judgments, constructional aparaxia, visual neglect (Funk et al., 2013; Kerkhoff, 1999), balance problems (Bonan et al., 2007), a tilted subjective postural vertical (Perennou et al., 2008), and a poor functional outcome of the individuals with stroke (Funk et al., 2013). Those results have been interpreted in favor of a multimodal, graviceptive–vestibular pathway proceeding from the brainstem via the thalamus to temporoparietal multisensory cortical areas, and in case of a lesion leading to perturbations of the visual vertical (Brandt et al., 1994; Baier et al., 2012) or the tactile vertical (Funk et al., 2010a, 2010b). Moreover, some researchers postulate, that the right cerebral hemisphere elaborates an *integrated* verticality representation across different modalities (Perennou et al., 2008). As a consequence, lesions of the right hemisphere, i.e. due to stroke, might compromise perception of the vertical in a multimodal way.

Abbreviations: GVS, galvanic-vestibular stimulation; SVV, subjective visual vertical; STV, subjective tactile vertical

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As the vestibular system plays a significant role in the computation of the subjective vertical, its activation may modulate the verticality perception. For this purpose electrical stimulation of the vestibular system can be induced by placing one electrode behind each ear over the left and right mastoid respectively (termed galvanic vestibular stimulation or GVS, for review see Utz et al., 2010). Underneath the mastoids the vestibular nerve projects from the inner ear to the vestibular brain stem nuclei, over thalamic nuclei to a number of distributed cortical vestibular areas including area 2cv near the central sulcus, area 3a, b in the somatosensory cortex, parietal area 7a, and the parieto-insular-vestibular-cortex (PIVC). Although there is no primary vestibular cortex as in the visual, auditory or tactile modality, the above mentioned array of multiple, interconnected vestibular cortical areas is thought to be under the control of the PIVC (Guldin and Grüsser, 1998). Practically, GVS consists of applying direct current to the mastoids – usually delivered by a small battery-driven constant current stimulator. The positive electrode is termed the anode, the negative the cathode. Consequently, the two following electrode combinations are typically used for GVS: left-cathodal/right-anodal (CL) and right-cathodal/left-anodal (CR) GVS. Subliminal GVS can be administered by adjusting the current intensity below an individual's sensory threshold. This has the methodological advantage that different GVS protocols and polarities can be manipulated elegantly without the patient's knowledge (whether real current is flowing or not) that might otherwise influence his/her performance due to "spatial cueing" effects induced by a tingling sensation under one electrode. Furthermore, GVS is painless, easily applicable, safe, and induces minimal side effects when used in accordance with standard safety guidelines (Utz et al., 2011c).

GVS as a stimulation method has significant effects on a wide variety of cognitive and perceptual tasks, both in healthy persons and neurological patients (for review see Utz et al., 2010). For example, Wilkinson and co-workers found that GVS facilitated visual memory recall in healthy persons (Wilkinson et al., 2008) and improved visuo-constructive deficits in a right-hemisphere lesioned patient (Wilkinson et al., 2010, 2014). Similar studies showed modulatory effects of GVS on somatosensory deficits (Schmidt et al., 2013a) and different components of visual neglect (Utz et al., 2011a, 2011b; Oppenländer et al., 2014) thus demonstrating multifaceted effects on neuropsychological functions or deficits.

The first study that assessed the influence of GVS on verticality perception in healthy subjects found a shift of the visual and tactile vertical towards the anode (Mars et al., 2001). In a recent study (Volkening et al., 2014) the SVV and STV shifted towards the anode during GVS, whereas this shift was reversed towards the cathode in both modalities once stimulation was turned off. Overall, the effects were strongest for the haptic modality. Evidence from a recent clinical study (Saj et al., 2006) in right-hemisphere lesioned patients with vs. without visual neglect showed that left-cathodal GVS reduced the constant error in the SVV. Whether GVS also affects performance in the STV is unknown, to the best of our knowledge. Moreover, performance of impaired persons in both sensory verticals (visual, tactile) is most often characterized by two features: a frequently observed directional error (= the counterclockwise or clockwise tilt in the frontal or roll plane) and/or a reduced precision or pathologically increased variability as indicated by raised difference thresholds or huge ranges in these tasks (Kerkhoff, 1999; Utz et al., 2011a). These latter types of errors are frequently observed in patients with a tilted SVV or STV (Funk et al., 2010b, 2013) and are significantly related to disturbed spatial behavior as well (i.e. line orientation judgments, Funk et al., 2013) or balance problems (Bonan et al., 2007). Hence, both from a theoretical and a clinical viewpoint, it would be important to know whether GVS modulates not only the constant (directional) errors but also those parameters that indicate a reduced precision and higher variability in the SVV and STV. Finally, we sought to analyze whether modulatory GVS effects occur *selectively* in patients with disturbed SVV/STV or are also found in those patients without a deficit in these sensory axes.

Our research questions for this study were hence threefold: 1) Does GVS modulate constant/directional errors in the SVV and STV? 2) Does GVS modulate the precision in the SVV/STV as expressed by difference thresholds and range of performance? 3) Are the modulatory effects induced by GVS specific for patients with an impaired SVV/STV or do significant effects also occur in patients who are unimpaired in these tasks?

2. Methods

2.1. Patients

The study was approved by the local ethics committee (Ärztekammer des Saarlandes, Nr. 147/08, 16.9.2008) and included 24 patients with unilateral right-sided stroke (Table 1). Inclusion criteria were right-handedness and a single right hemisphere infarction or hemorrhage. Exclusion criteria were other neurological or psychiatric diseases, epilepsy, a sensitive scalp skin and metallic brain implants (Iyer et al., 2005). The participants were 9 women and 15 men with a median age of 63.6 years (range 42–84 years), and a median time since lesion of 2 months (range: 1–84 months). Patients were allocated into an "impaired" or "unimpaired" group depending on their performance in the SVV or the STV tasks (described below) separately. Normative data for both tasks had already been collected in a previous study (Kerkhoff, 1999). The cut-off-score for the constant error was 2.0° for the SVV and 2.5° for the STV. Healthy controls did not participate in the present study (see Table 1).

For both the SVV and STV the patients were allocated to a patient group *with or without a spatial deficit in the SVV or STV* (termed impaired or unimpaired) depending on their performance in the sham condition in both tasks. Further information about the patient sample and additional clinical assessments (i.e. visual neglect, visual field, motor status) can be found in the companion paper in this special issue on "Brain stimulation and Attention" (see Oppenländer et al., 2014). The sample studied in the present study was identical to that in the companion paper. All patients had a corrected visual acuity for the near distance (0.4 m) of at least 0.7 (=70%, 7/10).

2.2. Experimental procedures

In the first session the stimulation threshold for GVS was determined in all subjects. After fixing the electrodes, galvanic bipolar stimulation was delivered by a constant direct current (DC) stimulator (9 voltage battery, Type: ED 2011, manufacturer: DKI GmbH, DE-01277 Dresden). The carbon-rubber electrodes (50 mm × 35 mm) were fastened on the skin over each mastoid (binaural stimulation), in order to activate the peripheral vestibular organs. The conditions were termed Cathode Left (CL) when the cathode was placed over the left mastoid and the anode on the right, and Cathode Right (CR) when polarization was inversed. Similar to others (Rorsman et al., 1999) we stimulated below the sensation threshold (subliminal) in order to prevent awareness of any electrical stimulation in the 3 experimental conditions. A switch on the stimulation device delivered current at individually adjusted levels for each patient. This threshold was individually determined in this first session by slowly increasing current intensity in steps of 0.1 mA until the participant indicated a tingling sensation (first threshold). The current was subsequently reduced

Table 1
Patient characteristics of 24 patients with unilateral right-hemispheric stroke. See text for details.

Patient	Age/ sex	Etiology	Lesion	TSL (months)	Hemi-paresis	Field defect	Subjective visual vertical[a]	Subjective tactile vertical[b]
1	55/m	I	F, T	4	Left	No	Impaired	Unimpaired
2	76/m	I	F, T, P	84	Left	HH	Unimpaired	Impaired
3	65/m	I	F, T, P, BG	3	Left	Q	Impaired	Impaired
4	65/m	I	T	15	Left	No	Unimpaired	Unimpaired
5	70/f	H	BG	2	Left	No	Impaired	Impaired
6	62/m	I	T	1	Left	No	Unimpaired	Impaired
7	59/m	I	P, O	1	No	No	Unimpaired	Unimpaired
8	72/f	I	T	2	Left	HH	Unimpaired	Unimpaired
9	50/m	I	T	2	Left	No	Unimpaired	Unimpaired
10	51/m	I	BG	1	Left	No	Unimpaired	Unimpaired
11	70/m	I	T	1	Left	No	Impaired	Impaired
12	67/m	I	T, F	1	Left	No	Unimpaired	Unimpaired
13	79/f	I	T, F	2	Left	No	Impaired	Impaired
14	84/f	I	F, T	12	Left	No	Unimpaired	Unimpaired
15	72/m	I	T, P	1	Left	Q	Unimpaired	Unimpaired
16	70/m	I	T	2	Left	No	Impaired	Impaired
17	70/m	I	F	35	Left	No	Impaired	Unimpaired
18	42/f	I	T, BG	1	No	No	Unimpaired	Unimpaired
19	76/f	I	F, T, P, O	1	Left	HH	Unimpaired	Impaired
20	53/f	I	O	3	No	HH	Unimpaired	Unimpaired
21	51/m	H	P	1	No	Q	Unimpaired	Unimpaired
22	57/f	H	T, P	3	Left	No	Unimpaired	Impaired
23	67/f	I	F	1	Left	No	Impaired	Unimpaired
24	44/m	H	F, T, P	3	Left	No	Unimpaired	Unimpaired
	Mean: 63.6 yrs	20 I, 4 H		Median: 2 month	20/24 im-paired	7/24 impaired	8/24 impaired	9/24 impaired

I/H: ischemic/hemorrhagic stroke; P/T/F/O/BG: parietal/temporal/frontal/ occipital/basal ganglia; TSL: time since lesion; HH: homonymous hemianopia, Q: quadrantanopia.
[a] Based on a cutoff-value of $+/-$ 2.0° for the constant error in this task derived from Kerkhoff (1999).
[b] Based on a cutoff-value of $+/-$2,5° for the constant error in this task derived from Kerkhoff (1999).

until the participant reported that the sensation had disappeared (second threshold). This procedure was repeated a second time and the median of these 4 threshold values was defined as the sensory threshold. This value of current intensity was then used for the CL and CR sessions. The mean threshold level across all patients was 0.7 mA (range: 0.4–1.5 mA). This strategy of subliminal GVS eliminates any "spatial cueing" effects as a consequence of the tingling sensation typically felt by the participant when *above-threshold* electrical current is delivered to the anode on the mastoid.

After the threshold determination for GVS all participants performed the two verticality tasks (SVV, STV; described below) *while* the electrodes of the stimulation device were fixed over the mastoids but not active, thus creating a sham condition. To this purpose, after fixing the electrodes, the current was initially turned on until the participant perceived a tingling sensation, after which the current was smoothly turned off within 30 s, without the patient being aware of this (due to the subthreshold stimulation, see above). The stimulator was always invisible for the participant. This created an effective sham-stimulation since the individuals were not able to discriminate between the conditions where real current was applied and those where the current was turned off due to the imperceptible sub-threshold intensity of the stimulus. In sessions 2 and 3, the patients repeated all experimental tasks, but received subliminal, *real* GVS (either CL or CR). The sequence of these 2 experimental conditions was counterbalanced within each group, with one half of the participants receiving CL in session 2 and CR in session 3, and the other half receiving the opposite sequence. The study design was single-blinded, i.e. only the participants were blinded for the experimental conditions (CL, CR, and Sham).

The three sessions were performed on three separate days. The total experiment was completed within 5 days. Each session lasted approximately one hour, but GVS stimulation was always limited to 20 minutes per session. GVS-stimulation started a few seconds before the task instruction by the experimenter and terminated immediately after completion of the two tests.

2.3. *Experimental verticality tests*

2.3.1. *Subjective visual vertical (SVV)*

The subjects were tested using specific software (VSWin; Kerkhoff and Marquardt, 1995) for the measurement of the SVV in the frontal or roll plane. VS is based on the method of limits (Engen, 1971). In the measurement of the SVV, the experimenter is required to orient an oblique white line (100 mmx2 mm) presented on a black background until the subject indicates that it lies exactly vertical. The line is then rotated further until the subject indicates that the line is no longer vertical. With this method, two psychophysical parameters are calculated: the constant error and difference threshold. The constant error denotes the difference between the subject's mean estimate (the point of subjective equality) and the objective correct orientation (here: 90°). Hence, the constant error gives information about the central tendency or central error of the subject. A positive constant error value represents a clockwise deviation from veridical and a negative value represents anticlockwise deviation. The interval of uncertainty indicates the complete range during which the subject considers the displayed line as exactly vertical within each trial. From this value the difference threshold is calculated which is defined as one half of the interval of uncertainty (Engen, 1971). Finally, the range was computed for each subject in this task which denotes the distance between the minimum and maximum score (across *all* trials). Ten trials were performed, 5 with a clockwise rotation and 5 with a counterclockwise rotation. The starting position was always 30° away from the objective vertical (hence either at 60° or 120°, while vertical was defined as 90°). The head and body of the subject were oriented earth-vertical within an experimental chair with a supporting head- and chinrest. All measurements were taken in total darkness with the chassis of the PC-monitor covered by an oval-shaped mask to eliminate any visual reference cues. No visual cues were visible except the bar for estimating the SVV. Subjects were tested at a distance of 0.5 m from a monitor with spectacle corrections where necessary. For the statistical analysis, the constant errors, difference thresholds and ranges (all in °) were analyzed.

2.3.2. *Subjective tactile vertical (STV)*

The STV was measured via a rotatable metal bar (15 cm long, 12 mm wide) which was fixed on a wooden board (0.4×0.5 m^2; Kerkhoff, 1999). The board was mounted perpendicularly on a table in front of the patient at a distance of 0.5 m. Participants were sitting on a chair with their head supported by a head-and chinrest such that his/her body and head were oriented earth-vertical. The rod was continuously adjustable in the frontal plane. A scale was drawn on the board, hidden from participants, indicating their tactile-spatial judgment in degrees. The scale ranged in steps of 1° from 0° indicating the right horizontal over 90° denoting the objective vertical to 180° indicating the left horizontal. Prior to each experimental session, the apparatus and rod were calibrated according to the earth vertical. Participants were required to adjust the bar blindfolded according to their subjective tactile vertical with their right (nonparetic) hand. There were two different starting positions, one 30° rotated from the veridical vertical in clockwise direction (120°), the other 30° rotated from the objective vertical in counterclockwise direction (60°). After 5 practice trials, participants had to perform 10 experimental trials, 5 from each starting position, their order pseudo-randomized. Participants were only allowed to touch the metal rod, not the outer edges of the board. The tactile-spatial tests were performed with the same experimental chair as in the SVV (see above) at a distance of 0.5 m from the tactile board. Subjects were blindfolded before starting the five practice trials per task (which were not counted) to familiarize the subjects with the tasks. Constant errors and ranges from the 10 measurements were calculated.

2.4. *Statistics*

For the analysis of stimulation effects on constant errors, range values and difference thresholds (only SVV), 2 × repeated-measures ANOVAs were conducted with the between-subjects factor group (impaired, unimpaired) and the within-subjects factor GVS (Sham, CR, CL), separately for each measure. The results of the ANOVAs were Greenhouse-Geisser corrected when sphericity was violated according to significant Mauchly-Tests.

3. Results

3.1. *Subjective visual vertical (SVV)*

Repeated measures ANOVAs revealed a main effect of GVS on constant error [$F(2, 44)=12.03$, $p<.001$, $\eta_p{}^2=.35$], difference threshold [$F(1.19, 26.11)=5.55$, $p=.02$, $\eta_p{}^2=.20$] and range [$F(2, 44)=11.69$, $p<.001$, $\eta_p{}^2=.35$], each with the lowest values under CL stimulation. Concerning the constant error, there was a main effect of group [$F(1, 22)=26.80$, $p<.001$, $\eta_p{}^2=.55$], indicating the impaired group having a greater error reduction depending on the experimental manipulation as compared to the unimpaired group. Additionally, the interaction between both variables on constant error values was also significant [$F(2,44)=7.05$, $p=.002$, $\eta_p{}^2=0.24$] showing that the impaired group had a higher benefit of GVS under CL-stimulation than the unimpaired group. Pairwise comparisons showed the error reduction in the RBD+ group to be significantly lower under CL- as compared to Sham-stimulation [$t(7)=$ 5,79, $p=.001$, $r=.91$] as well as marginal significantly lower under CL- as compared to CR-stimulation [$t(7)=-1.98$, $p=.08$]. Across both groups, difference thresholds were significantly lower under CL-stimulation than under sham stimulation [$t(23)=2.70$, $p=.01$, $r=.49$] as revealed by post-hoc comparisons. There additionally was a numerical, though non-significant trend towards reduced thresholds in the CR as compared to the Sham/Baseline condition [$t(23)=1.83$, $p=.08$]. Concerning range, post-hoc analyzes revealed a significantly greater reduction in the CL [$t(23)=$ 2,48, $p=.02$, $r=.46$] and the CR condition [$t(23)=$ 2,68, $p=.01$, $r=.49$] for both groups as compared to sham stimulation.

Fig. 1 illustrates the influence of GVS on error, threshold and distribution (range) values in both patient groups.

3.2. *Subjective tactile vertical (STV)*

There was a non-significant trend to an interaction between GVS and group on constant error [$F(1.25, 27.55)=3.76$, $p=.055$, $\eta_p{}^2=.15$] indicating that error values were the lowest under CL stimulation in both groups (see Fig. 2). Concerning range, repeated measures ANOVAs revealed no significant effects. However, there was a numerical trend towards lower range values under GVS stimulation in the impaired as compared to the unimpaired group (see Fig. 2).

4. Discussion

Several findings are apparent from our study: 1) CL-GVS, but less CR-GVS influenced the SVV and STV in patients who were impaired in these tasks. 2) GVS affected not only constant errors,

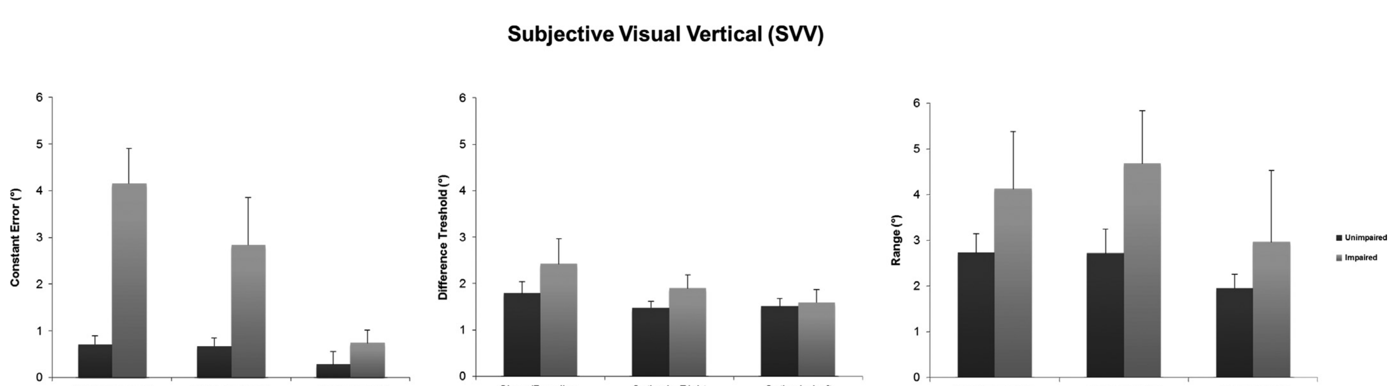

Fig. 1. Results of GVS on the SVV (constant errors, difference thresholds, range, all in °) across the three experimental conditions (Sham; cathode right=CR, cathode left=CL). Error bars indicate 1 SEM. See text for details.

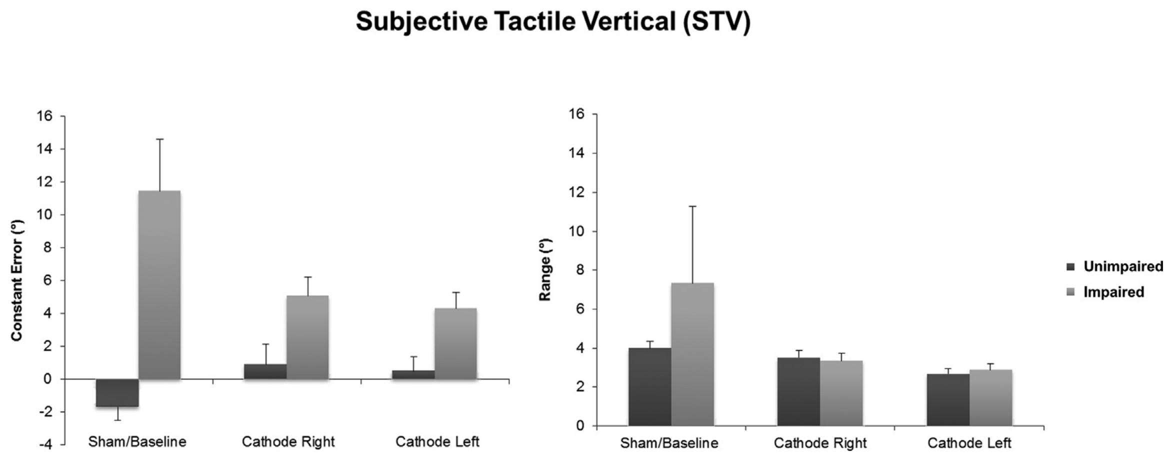

Fig. 2. Results of GVS on the STV (constant errors, range, all in °) across the three experimental conditions (Sham; cathode-right = CR, cathode-left = CL). Error bars indicate 1 SEM. See text for details.

but also difference thresholds and ranges in the SVV. Similar effects were seen for the STV, but did not reach statistical significance.

4.1. SVV

Our results are in accordance with those of Saj et al. (2006) who also found a reduction of the constant error with CL-GVS in right-hemisphere stroke patients. Furthermore, the present study extends these findings by showing that the same positive effect is also found for the difference thresholds and ranges, which decreased significantly with CL-GVS. This shows that GVS not only influences the directional error (hence the tilt), but also improves the general spatial precision in the tasks, regardless of the direction of the tilt. Put differently: the patients were much more accurate and consistent in the task when stimulated with GVS. This observation is clinically relevant as it shows that the frequently observed large variability of patients with right-sided stroke in visuo-spatial or tactile-spatial perceptual judgments (Kerkhoff, 1999; Funk et al., 2013) can be significantly reduced by vestibular input. This offers therapeutic options in neurorehabilitation, as GVS could be applied in addition to behavioral–perceptual treatments (i.e. Funk et al., 2013).

4.2. STV

We found largely the similar pattern of results for the STV as for the SVV, with one exception: the deviations in the latter were typically larger than in the prior, which is related to the fact that tactile estimation is more difficult than visual judgement of the verticality in the roll/frontal plane. This nicely agrees with similar findings from visual and tactile vertical tests of other studies (Kerkhoff, 1999; Utz et al., 2011a; Funk et al., 2010a, 2010b). Moreover, the modulatory effect of GVS largely to be similar in the tactile as in the visual modality (in terms of reduction of the errors in °), although the reduction of the range values were not significant for the STV in the impaired group (Fig. 2). This latter finding is probably due to the large variabilities in our data which might have prevented significant effects for the range values. Nevertheless, the current data are in agreement with the GVS-modulatory effect on the STV found in studies with normal subjects and higher current values as the present (Mars et al., 2001; Volkening et al., 2014). This shows a strong influence of vestibular input onto the somatosensory system and is in accord with similar GVS-modulatory effects on tactile extinction (Schmidt et al., 2013b). Anatomically, this influence may result from the partially overlapping cortical projection zones of the vestibular and somatosensory systems that terminate in the parietal lobe (Lopez et al., 2012), so that vestibular stimulation also activates in parallel the somatosensory system.

4.3. Implications

In accordance with previous studies for the SVV (Saj et al., 2006) and similar studies in visual neglect (Oppenländer et al., 2014) our results show that *subliminal* GVS is a promising and effective technique for non-invasive, bottom-up stimulation of brain damaged patients with multimodal spatial disorders of verticality. The technique is easy to administer, low-cost, safe, and has been shown to modulate a wide range of neurocognitive or neurosensory functions transiently (Utz et al., 2010 for review). A recent study showed *lasting* effects of a small number of repetitive GVS sessions on tactile extinction (Schmidt et al., 2013b), thus showing its feasibility and efficacy of repetitive GVS as a treatment. In this sense we would expect that *repetitive* GVS could permanently recalibrate the distorted visual and tactile vertical in patients suffering from right-hemisphere stroke – but this hypothesis has to be tested in subsequent studies. Repetitive GVS might also speed up the recovery from the marked balance problems so often reported for this patient group (Bonan et al., 2007).

4.4. Limitations of the study

As a limitation of our study, we cannot completely rule out practice effects as sham stimulation was always administered first. However, some of our findings argue against that possibility: first, the unimpaired unimpaired patient group did not show any improvement, which theoretically could have occurred in their results (because they were not perfect in the tasks). Second, we found that CL-GVS had the strongest effect on all parameters of both axes, regardless of whether this was the second or third session (given that the two real GVS stimulation sessions were pseudo-randomized in their sequence). This speaks against a practice or mere repetition effect. Taken together, even if we cannot completely rule out the contributing effects of test practice, these appear unlikely. Moreover, the thresholding procedure for GVS in the beginning of the Sham session could have influenced the results, although it lasted only 30 s. This could have been circumvented by adding another (fourth) session devoted only to the threshold determination 1 or 2 days before starting with the sham-session. This was not possible due to time constraints in the neurorehabilitation setting. Nevertheless, sham GVS was less effective or completely ineffective as compared to *real* GVS thus highlighting the specificity of the latter. Moreover, the subliminal stimulation excluded any subtle attentional cueing effects arising from the tingling of the active electrode that are inevitable with suprathreshold GVS.

5. Conclusions

Subliminal GVS significantly reduces the tilt and improves the general precision in the SVV and STV in individuals with right-sided stroke.

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