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How the vestibular system interacts with somatosensory perception: A sham-controlled study with galvanic vestibular stimulation

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HIGHLIGHTS

- Left anodal galvanic vestibular stimulation increased tactile sensitivity.
- No effects induced by sham stimulation or right anodal galvanic vestibular stimulation.
- Even brief (100 ms) pulses of vestibular stimulation enhanced somatosensory detection.
- Vestibular projections in the right hemisphere modulates somatosensory processing.

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ABSTRACT

The vestibular system has widespread interactions with other sensory modalities. Here we investigate whether vestibular stimulation modulates somatosensory function, by assessing the ability to detect faint tactile stimuli to the fingertips of the left and right hand with or without galvanic vestibular stimulation (GVS). We found that left anodal and right cathodal GVS, significantly enhanced sensitivity to mild shocks on either hand, without affecting response bias. There was no such effect with either right anodal and left cathodal GVS or sham stimulation. Further, the enhancement of somatosensory sensitivity following GVS does not strongly depend on the duration of GVS, or the interval between GVS and tactile stimulation. Vestibular inputs reach the somatosensory cortex, increasing the sensitivity of perceptual circuitry.

1. Introduction

The cortical vestibular system is strongly integrated with other sensory modalities, including somatosensory processing [14]. We previously reported that cold caloric vestibular stimulation (CVS) increases tactile sensitivity on the fingers of both hands [4,6]. Additionally, somatosensory potentials evoked by median nerve stimulation are modulated by CVS [5]. In particular, CVS selectively enhanced the N80 component recorded over both ipsilateral and contralateral somatosensory areas, without significantly affecting earlier or later components. Interestingly, the N80 component has been localised to the parietal operculum (OP) [10], which includes the human homologue of the monkey parieto insular vestibular cortex (PIVC) [3,14,22], and is thus a prime neuroanatomical candidate for vestibular-somatosensory convergence [5].

However, CVS has important methodological limitations [15]. During CVS participant's ear is irrigated with cold water for few seconds. This technique does not permit a complete control of the parameters of the stimulation, for example the exact volume of water going into the external ear canal and the precise timing of the stimulation of the vestibular organs. Moreover, non-vestibular contributions to CVS-induced modulation of somatosensory processing, for example due to the cold sensation in the outer ear, cannot be ruled out, because of the absence of reliable sham stimulation.

Here the vestibular modulation of somatosensory perception is investigated using a well-controlled, quantitative method for activating the vestibular cortical projections. Galvanic vestibular stimulation (GVS) is a non-invasive technique [19] that involves a weak direct current passing between surface electrodes placed on the mastoid behind the ear [8]. GVS modulates the firing rate of vestibular afferents with perilymphatic cathodal currents causing an increase in firing rate and anodal currents causing a decrease [8].

Abbreviations: CVS, caloric vestibular stimulation; GVS, galvanic vestibular stimulation; EPSPs, excitatory postsynaptic potentials; OP, parietal operculum; SII, secondary somatosensory cortex; PIVC, parieto insular vestibular cortex; SSDT, somatosensory signal detection task.

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Bipolar binaural GVS evokes a net pattern of firing across both vestibular organs that mimics a head motion in space [9]. Crucially, the polarity of stimulation can be reversed as part of the experimental procedure, producing opposite effects on firing rate in the two vestibular organs, and thus reversing of direction of the apparent head motion. Moreover, placing the GVS electrodes away from the mastoids allows a sham stimulation, producing the same skin sensations under the electrodes as real GVS, but without stimulation of the vestibular organs.

In the present study, we assessed effects of vestibular inputs on somatosensory perception by administering different GVS polarities and a sham condition (Experiment 1). We also explored the time-course of the vestibular-somatosensory interaction (Experiment 2).

2. Experiment 1: specificity of vestibular-somatosensory interaction

2.1. Participants

Twelve naïve paid participants volunteered in Experiment 1a (8 male, ages: 20–32 years, mean ± SD: 24.41 ± 3.94 years), in Experiment 1b (10 male, ages: 20–32 years, mean ± SD: 22.91 ± 3.80 years), and in Experiment 1c (10 male, ages: 20–32 years, mean ± SD: 22.91 ± 3.80 years). Six of those who participated in Experiment 1a also participated in Experiment 1b and Experiment 1c. All participants were right-handed [17] with no history of neurological disorders. The experimental protocol was approved by University College London research ethics committee.

2.2. Galvanic vestibular stimulation procedure

GVS was applied in bipolar configuration by a custom-built constant-current stimulator (Good Vibrations Engineering Ltd., Nobleton, Ontario, Canada) used to deliver a boxcar pulse of 1 mA (duration is given below for each experiment, see Sections 2.3 and 3.2). Carbon rubber electrodes (area 10 cm^2) coated with electrode gel were placed binaurally over the mastoid processes and fixed in place with adhesive tape. Left anodal and right cathodal configuration was named 'LGVS' (Experiment 1a). The inverse polarity, namely left cathodal and right anodal configuration, was named 'RGVS' (Experiment 1b). Sham stimulation was applied in which the electrodes were placed on the left and right side of the neck (about 5 cm below the GVS electrodes) using left anodal and right cathodal configuration (Experiment 1c). This causes a similar tingling skin sensation to real GVS, so it functions as a sham control for non-vestibular effects. Such non-vestibular effects could include a direct somato-somatosensory interaction between the skin sensations generated by the GVS electrodes and by the finger electrodes, and also more general factors such as the knowledge that an unusual stimulation is occurring.

2.3. Somatosensory signal detection task (SSDT)

Participants performed a somatosensory signal detection task (SSDT) during LGVS (Experiment 1a), RGVS (Experiment 1b) and sham stimulation (Experiment 1c). The methods closely followed a previous study [4]. SSDT was administered using a repeated measure design with stimulation (off-stimulation vs on-stimulation), side of tactile stimulation (left finger vs right finger) as within-subject variables.

Tactile stimulation was provided by a custom-built electrical stimulator, whose current-level and pulse duration were controlled by a computer. Tactile stimuli were delivered via 4 mm diameter concentric electrodes [11] attached to the index fingertips by surgical tape. A staircase procedure [13] was used to estimate the tactile threshold and this value was used to determine the intensity of the tactile stimuli during the SSDT. Our design factorially combined GVS and tactile stimulation conditions. SSDT consisted of sixty trials at current levels slightly below estimated tactile threshold (−10%) and 60 catch trials. We also delivered 20 trials at current levels clearly above tactile detection (+10%). These above-threshold trials were intended to remind participants of the nature of the tactile signal being detected, and were not analysed further [4]. Trials were delivered both in an on-stimulation condition, and an off-stimulation condition in which the vestibular/sham current was zero. All combinations of GVS and tactile stimulation were randomised anew for each experiment and each participant.

The beginning of each trial was signalled by an auditory tone. For on-stimulation trials, vestibular/sham stimulation was delivered after a variable interval between 250 ms and 500 ms from the acoustic sound. Vestibular/sham stimulation was followed by 1000 ms of delay and then the cutaneous shock, if present, was administered. A different tone indicated the end of the trial after 500 ms of delay from the cutaneous shock. In each on-stimulation trial the overall duration of vestibular/sham stimulation was 1500 ms. Participants were required to indicate whether or not they felt the tactile stimulus. Off-stimulation trials had an identical timing, but no actual vestibular/sham stimulation current.

In Experiment 1a SSDT was performed in different body postures. In one condition, participants were asked to sit upright with a normal head posture. In a second condition, participants sat with the hips and neck flexed, in a head-down posture. This is known to maximise the effect of GVS by aligning Reid's plane with the vertical plane [2]. Experiment 1b and Experiment 1c were performed with head down postures.

The data from catch trials and from trials with intensity just below threshold were analysed using signal detection analysis [16]. The d' measures of sensitivity, and the C measure of response bias were calculated for each participant in each condition. The same false alarm rate was used for both left and right fingers, so the d' values for the two fingers are not fully independent, since they both include this common term.

2.4. Results

2.4.1. Experiment 1a: LGVS

SSDT estimates of perceptual sensitivity (d') and response bias (C) were analysed using 2 × 2 × 2 repeated measure ANOVA with factors of Stimulation (on-stimulation vs off-stimulation), Side of tactile stimulation (left hand vs right hand) and Body Posture (head-down vs head-natural) (Fig. 1).

Analysis of d' showed a significant effect of Stimulation ($F_{(1,11)} = 5.020$, $p = 0.047$), with better tactile sensitivity when GVS was on than when it was off. There was no effect of Side ($F_{(1,11)} = 0.102$, $p = 0.755$) and no effect of Head Posture ($F_{(1,11)} = 1.245$, $p = 0.288$). No interactions between factors were significant (all $p > 0.05$). C values showed no significant main effect of Stimulation ($F_{(1,11)} = 0.487$, $p = 0.500$), or Side ($F_{(1,11)} = 0.017$, $p = 0.898$) or Head Posture ($F_{(1,11)} = 2.207$, $p = 0.165$). A significant interaction between Stimulation and Head Posture was found ($F_{(1,11)} = 10.249$, $p = 0.008$). This interaction was not predicted, but is reported here for completeness. Simple effects analysis was used to explore this interaction, holding the level of each factor constant and investigating the effects of the other factor. Thus, there was a significant difference between head-down posture and natural head posture ($t_{(11)} = -3.235$, $p = 0.008$) for the off-stimulation condition, but not for the on-stimulation condition ($p > 0.05$). No other significant comparisons were found.