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Concurrent visual and tactile steady-state evoked potentials index allocation of inter-modal attention: A frequency-tagging study

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HIGHLIGHTS

- Steady-state evoked potentials (SSEPs) indexed concurrent visuo-tactile processing.
- Inter-modal selective attention influenced SSEP amplitude and phase.
- Patterns of SSEP modulation differed between vision and touch.

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ABSTRACT

We investigated effects of inter-modal attention on concurrent visual and tactile stimulus processing by means of stimulus-driven oscillatory brain responses, so-called steady-state evoked potentials (SSEPs). To this end, we frequency-tagged a visual (7.5 Hz) and a tactile stimulus (20 Hz) and participants were cued, on a trial-by-trial basis, to attend to either vision or touch to perform a detection task in the cued modality. SSEPs driven by the stimulation comprised stimulus frequency-following (i.e. fundamental frequency) as well as frequency-doubling (i.e. second harmonic) responses. We observed that inter-modal attention to vision increased amplitude and phase synchrony of the fundamental frequency component of the visual SSEP while the second harmonic component showed an increase in phase synchrony, only. In contrast, inter-modal attention to touch increased SSEP amplitude of the second harmonic but not of the fundamental frequency, while leaving phase synchrony unaffected in both responses. Our results show that inter-modal attention generally influences concurrent stimulus processing in vision and touch, thus, extending earlier audio-visual findings to a visuo-tactile stimulus situation. The pattern of results, however, suggests differences in the neural implementation of inter-modal attentional influences on visual vs. tactile stimulus processing.

1. Introduction

Despite the huge amount of information to which we are constantly exposed, our limited processing resources enable us to process a rather small fraction of information at a time. Therefore, the human brain is often forced to select information arising from a specific sensory modality to the detriment of other senses. This state of *inter-modal* attention has been shown to modulate behavioural measures of stimulus processing [4] as well as event related potentials (ERPs; [5,6,14]) and evoked gamma band responses [10] of the human electroencephalogram (EEG). In general, these findings showed that stimuli gained a processing advantage when they were presented to an attended sensory modality. Audio-visual inter-modal attention has recently been investigated by means of the frequency-tagging approach [8,12,13,21]. This method takes advantage of a type of electrophysiological brain response known as steady-state evoked potential (SSEP): a periodic stimulus presented with a defined temporal frequency elicits a quasi-sinusoidal brain response. SSEPs oscillate at the stimulus frequency (fundamental frequency), which allows to frequency-code concurrent stimuli in different sensory modalities and, thus, to trace corresponding EEG responses. SSEPs usually further comprise a second harmonic response, that is, a component oscillating at twice the stimulus frequency. Fundamental and second harmonic responses have been repeatedly found to reflect different aspects of stimulus processing (e.g. [1,16,21]).

Crucially, attention modulates SSEP amplitudes [7,18,19] and increases phase synchronisation [11,15] thus providing an index of attentional allocation to specific stimuli, i.e. sensory modalities. In line with results of ERP studies, audio-visual SSEP studies [13,21] observed greater SSEP amplitudes when the sensory modality of the corresponding driving stimulus was attended as compared to when it was unattended.

Despite the advantages provided by frequency-tagging, up to date, inter-modal attention effects on visual and *tactile* processing have been found and described almost exclusively in

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ERP paradigms (cf. [6,10], but see [23]). In the present study, we aimed to extend latter findings by employing SSEPs in a visuo-tactile experimental setting. In contrast to ERP paradigms, our approach allowed us to present visual and tactile stimuli simultaneously over extended periods of time while still being able to track the processing of each individual stimulus. Therefore, we were able to test whether sustained inter-modal attention influenced ongoing concurrent visual and tactile processing beyond transient effects as reflected in ERPs and evoked GBRs. Attentional influences were assessed by means of visual and tactile SSEP amplitude as well as phase synchronisation. Moreover, we compared inter-modal attention effects on fundamental responses and corresponding second harmonics as the functional relationship between the two responses is still debated [16]. Both SSEP components have been shown before to modulate differently under the influence of inter-modal attention; Saupe et al. [21], for instance, observed a systematic modulation in the second harmonic of the visual SSEP amplitudes, only.

Here, we presented concurrent visual and tactile stimuli, frequency-tagged at 7.5 Hz and 20 Hz, respectively. Participants were cued, on a trial-by-trial basis, to attend to the visual or the tactile stimulus while performing a task in the relevant modality. We hypothesised that SSEP amplitudes and phase synchronisation of the fundamental frequencies and the second harmonics were greater when the driving stimulus was attended as compared to when it was unattended.

We found that attention modulated visual SSEP amplitudes of the fundamental frequency (7.5 Hz), while the second harmonic (15 Hz) was not modulated. The opposite scenario was observed in tactile SSEPs, where the 20 Hz SSEP component did not show a consistent attentional modulation, while the second harmonic (40 Hz) was modulated systematically. We further observed modulations of phase synchrony for visual SSEPs, exclusively. Therefore, as expected, inter-modal attention generally modulated visual as well as tactile processing in our experiment. However, our results also point towards differences of how inter-modal attentional influences are conveyed in both modalities.

2. Materials and methods

Sixteen right-handed participants (range of age: 19–36, 10 women) took part in the experiment. Due to the absence of a visual 7.5 Hz SSEP above noise level, one participant was excluded from further analysis. Participants had normal or corrected to normal vision; none of them reported a history of neurological diseases. All procedures were in accordance with the Declaration of Helsinki, and approved by the local ethics committee. Prior to the experiment, participants gave informed written consent. They received course credits or monetary compensation.

Participants were comfortably seated in an acoustically dampened and electromagnetically shielded chamber in front of a 19″ cathode ray tube (CRT) screen at a distance of 80 cm, set to a refresh rate of 60 Hz. Participant's right hand was positioned on a table in front and aligned with the sagittal midline of the participant's body. A small electromagnetic stimulator (Dancer Design, St. Helen) was attached to the first phalanx of the index finger to deliver vibratory stimulation (see tactile stimulus description below). The stimulated hand was concealed in order to avoid any visual influence on tactile stimulus processing. The left hand served as the responding hand and was placed on a keyboard positioned left on the table. In order to mask the stimulator sound, white noise (intensity = 72 dB sound pressure level) was played through headphones for the entire block duration.

A rapid serial visual presentation (RSVP) of grey Gabor patches (diameter = ~6.5° of visual angle, spatial frequency = ~1.2 Hz/°, Fig. 1), with varying orientations, was centrally displayed on a grey background (~36.40 cd/m^2). A red dot (0.15°) superimposed on the RSVP centre served as fixation point. The rate of the RSVP was set to 8 cycles per second (=7.5 Hz), each cycle of which consisted of 8 frames (=133 ms). Gabor patches were shown during the first four frames of a cycle to produce a 50/50 on/off luminance flicker.

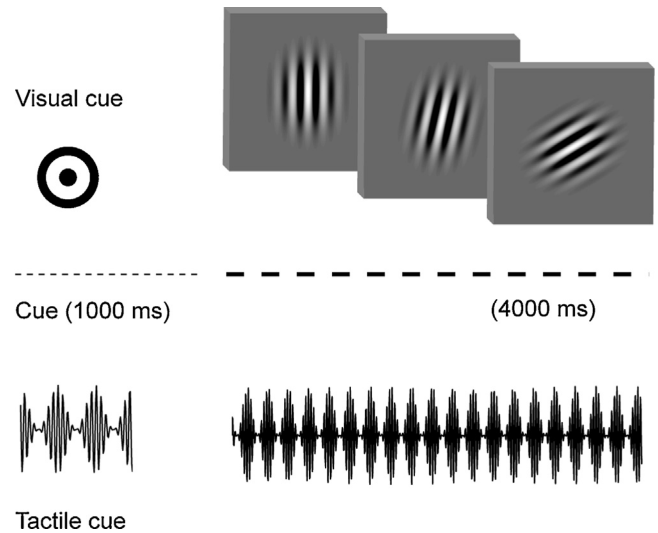

Fig. 1. Schematic illustration of a typical trial. Trials started with the presentation of a visual or tactile cue. Subsequently, concurrent visual and tactile stimulus streams were presented.

With each presentation cycle, Gabor patch orientation changed by a fixed step of 3° in clockwise or anti-clockwise direction following a random walk rule. The starting orientation was randomly chosen from a set of 60 different orientations (0–180° in steps of 3°). Occasionally, a target, consisting of a larger step (15°; duration = 67 ms) occurred and participants were instructed to give accurate speeded responses by a button press upon detection.

The tactile stimulus stream consisted of a 20 Hz amplitude-modulated (AM) wave delivered to the right index finger with a maximum force of ~0.19 N. The AM wave was obtained as the product of a 157 Hz carrier frequency and 20 Hz sine (Fig. 1). Participants were asked to detect short (100 ms) unpredictable decreases of the carrier frequency to 80 Hz; these targets were inserted within the carrier sinusoid before the latter was modulated by the 20 Hz sinusoid. As for the visual task, participants were instructed to give accurate speeded responses by button press.

Each trial started with the simultaneous presentation of a central red fixation point (0.15°) and a visual or tactile cue. The visual cue consisted of a white circle (diameter = 1°, width = 0.1°, duration = 1000 ms) surrounding the fixation point. The tactile cue consisted of a short (100 ms) salient vibration with the same magnitude as the stimulus stream. When the tactile cue was presented, the circle was absent and vice versa. After cue presentation, participants were instructed to maintain attention to the cued modality for 4000 ms, during which they were engaged in a detection task (see task descriptions). Participants were instructed to keep their gaze on the fixation point regardless of the condition. At the end of each trial a white "X" (1000 ms) was presented to allow participants to blink. After each block, participants received feedback upon their performance (percentage of hit rates and false alarms).

The experiment was subdivided into 8 blocks. Each block consisted of 40 trials (20 trials per condition). Within blocks, trials of the two experimental conditions "attend vision" and "attend touch" were presented in randomised order. Prior to EEG recording, each participant practised visual and tactile tasks for at least 2 blocks.