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Audio-visual synchrony and spatial attention enhance processing of dynamic visual stimulation independently and in parallel: A frequency-tagging study

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ABSTRACT

The neural processing of a visual stimulus can be facilitated by attending to its position or by a co-occurring auditory tone. Using frequency-tagging, we investigated whether facilitation by spatial attention and audio-visual synchrony rely on similar neural processes. Participants attended to one of two flickering Gabor patches (14.17 and 17 Hz) located in opposite lower visual fields. Gabor patches further "pulsed" (i.e. showed smooth spatial frequency variations) at distinct rates (3.14 and 3.63 Hz). Frequency-modulating an auditory stimulus at the pulse-rate of one of the visual stimuli established audio-visual synchrony. Flicker and pulsed stimulation elicited stimulus-locked rhythmic electrophysiological brain responses that allowed tracking the neural processing of simultaneously presented Gabor patches. These steady-state responses (SSRs) were quantified in the spectral domain to examine visual stimulus processing under conditions of synchronous vs. asynchronous tone presentation and when respective stimulus positions were attended vs. unattended. Strikingly, unique patterns of effects on pulse- and flicker driven SSRs indicated that spatial attention and audiovisual synchrony facilitated early visual processing in parallel and via different cortical processes. We found attention effects to resemble the classical top-down gain effect facilitating both, flicker and pulse-driven SSRs. Audio-visual synchrony, in turn, only amplified synchrony-producing stimulus aspects (i.e. pulse-driven SSRs) possibly highlighting the role of temporally co-occurring sights and sounds in bottom-up multisensory integration.

1. Introduction

Behavioral goals, as well as the physical properties of sensory experiences, shape how neural processes organize the continuous and often rich influx of sensory information into meaningful units. One such process, selective attention, serves to prioritize currently behaviorally relevant sensory input while attenuating irrelevant aspects (Posner et al., 1980; Treisman and Gelade, 1980). In a visual search display, for example, items matching the color or orientation of a pre-defined target stimulus undergo prioritized processing relative to other items (Treisman and Gelade, 1980; Wolfe, 1994; Wolfe et al., 1989).

Another process exploits the spatial and temporal structure of dynamic sensory input, extracting regularities either in the visual modality alone (Alvarez and Oliva, 2009; Lee, 1999) or, by cross-referencing co-occurrences across sensory modalities (Fujisaki and Nishida, 2005). In fact, aforementioned visual search can be drastically improved by presenting a spatially uninformative tone pip that coincides (repeatedly) with a sudden change in target appearance in a dynamic search array (Van der Burg et al., 2008).

This pop-out effect has been ascribed to a gain in relative salience of the target stimulus caused by the unique integration of auditory and visual information. The impression of a multisensory object hereby hinges on the temporal precision of coinciding unisensory inputs, also termed audio-visual synchrony, a critical cue for multisensory integration (Werner and Noppeney, 2011). Consecutive synchronous co-occurrences of the same auditory and visual stimulus components further increase the likelihood of multisensory integration (Parise, 2012).

Generalizing this multisensory effect to our everyday experience of

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dynamic cluttered visual scenes, Talsma et al. (2010) put forward that multisensory objects tend to involuntarily attract attention towards their position. As a consequence, they would gain an automatic processing advantage over unisensory stimuli. In a task that requires a sustained focus of attention on a specific position in the visual field multisensory stimuli may then act as strong distractors (Krause et al., 2012) because they withdraw common processing resources from the task-relevant focus of attention.

Interestingly, this influence seems to work both ways: As Alsius et al. (2005) have shown focusing on a visual task impedes the integration of concurrent but irrelevant visual and auditory input. This effect has been related to the concept of the temporal binding window, a period during which co-occurring attended visual and auditory stimuli are most likely to be integrated (Colonius and Diederich, 2012, Cecere et al., 2017). The window can expand for stimuli appearing at attended locations but remains unaffected (or contracts) when spatial attention is averted (Donohue et al., 2015).

Both phenomena - the involuntary orientation of spatial attention towards multisensory events as well as impeded multisensory integration when maintaining focused attention - have largely been studied in isolation (Talsma et al., 2010). We frequently encounter situations, however, in which the two biases can act concurrently. Moreover, they may fluctuate between having conjoined and conflicting effects depending on whether attended positions and multisensory events overlap or diverge in the visual field (that is in addition to their own inherent temporal variability (Keil et al., 2012)).

This complex interplay therefore warranted a dedicated investigation in a paradigm that allowed contrasting both cases directly. In the present study, we manipulated trial by trial whether participants attended to a dynamic audio-visual synchronous stimulus while leaving a concurrently presented asynchronous stimulus unattended or vice versa.

We probed early cortical visual processing by tagging stimuli with distinct temporal frequencies (Norcia et al., 2015; Regan, 1989). This frequency-tagged stimulation elicited periodic brain responses, termed steady-state responses (SSRs). SSRs index continuous processing of individual stimuli in multi-element displays and have been demonstrated to indicate the allocation of spatial attention (Kim et al., 2007; Müller et al., 1998a; Walter et al., 2012) as well as audio-visual synchrony (Jenkins et al., 2011; Keitel and Müller, 2015; Nozaradan et al., 2012).

Crucially, employing frequency-tagging allowed us to tease apart the relative facilitating effects of both factors as follows: Our paradigm featured two Gabor patches, one per lower visual hemifield, that each displayed two rhythmic physical modulations: As in classical frequency-tagging experiments they displayed a simple on-off flicker at different rates (14.17 and 17 Hz, respectively). Additionally, spatial frequencies of the Gabor patches modulated at slower rates (3.14 and 3.62 Hz, respectively), which gave the impression of a pulsation-like movement (see Fig. 1). We exploited this pulsation to introduce audio-visual synchrony with a concurrently presented tone that carried a frequency modulation with the same temporal profile as one of the visual stimulus' movement (Giani et al., 2012; Hertz and Amedi, 2010 for similar approaches; see Keitel and Müller, 2015). Participants were then cued randomly on each trial to attend to one of the two stimulus positions, while one of the two Gabor patches pulsed in synchrony with the tone. This paradigm enabled comparisons of SSR-indexed visual processing between four cases of Gabor patch presentation: attended synchronous

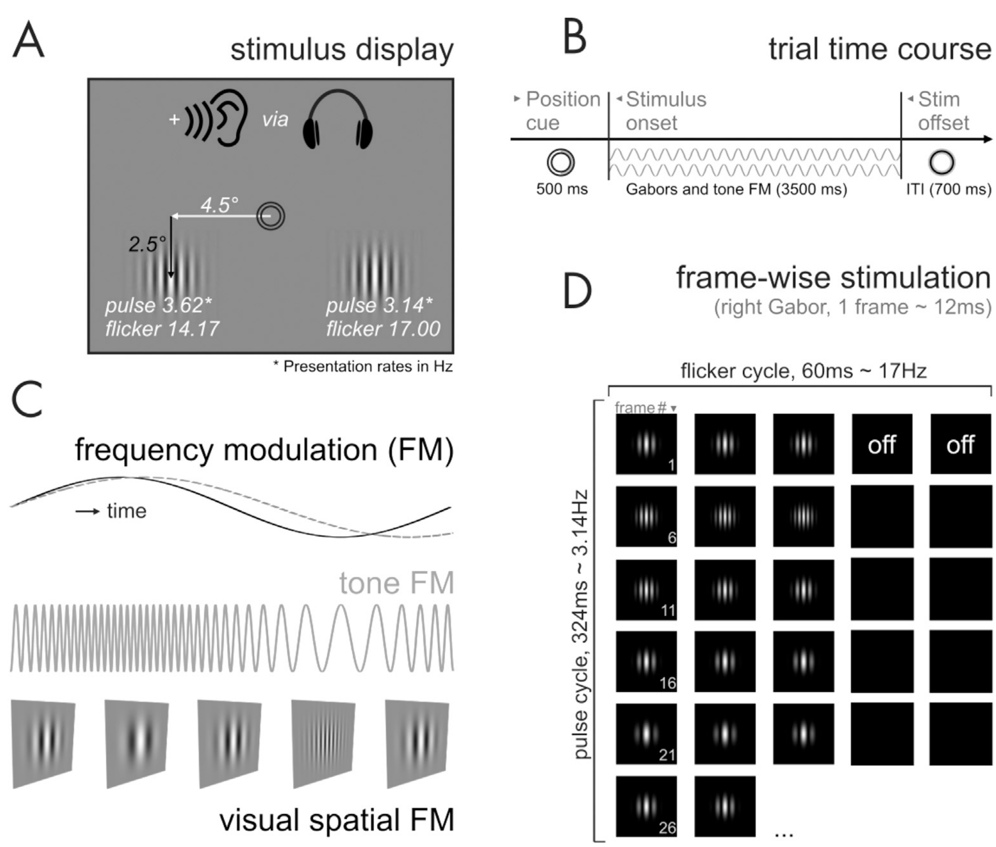

Fig. 1. Stimulation details. (A) On-screen stimulus display comprising central fixation rings and one Gabor patch per lower left and right visual hemifield. All items not to scale. Participants received auditory stimulation via headphones. (B) Schematic trial time course. An instructive position cue allocates attention to the left or right stimulus. Subsequent ongoing Gabor-patch and tone stimulation are represented by grey sinusoids. (C) A common frequency modulation (FM; solid black line) of auditory tone pitch and the spatial frequency of one of the two Gabor patches produces a synchronous pulsing audio-visual percept. Concurrently, the spatial frequency of the other Gabor patch modulates at a slightly different frequency (dashed grey line), thus rendering it asynchronous to the tone. (D) Frame-by-frame visual stimulation for the right Gabor patch. The illustration shows the first 27 frames of each trial. Note the emphasis on the on–off cycles leading to a 17-Hz flicker along the horizontal axis (black boxes = off-frames) and one full cycle of the spatial frequency modulation leading to a 3.14-Hz 'pulsation' along the vertical axis.

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