

# Brain signatures of auditory attention in real-life listening scenarios

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## Summary

Selective attention to relevant acoustic stimuli is critical for scene analysis and communication. Laboratory studies observe two major oscillatory brain processes that index auditory attention. First, slow neural oscillations (~4 Hz) reveal the brain's tracking of relevant acoustic stimuli. Second, the power of alpha oscillations (~10 Hz) indexes attention deployment to overcome listening challenges. In recent years, we found that investigation of these brain processes in more real-life listening scenarios significantly advances auditory attention research. Portable Electroencephalography (EEG), recorded inside the ear canal, reveals which sound source a listener attends to and is thus relevant for the development of future hearing aids. Furthermore, EEG recordings signify a listener's attentional suppression of stationary but also moving distractor sounds in a 360° loudspeaker array. While previous spatial attention studies often used rather unrealistic dichotic listening setups with competing sounds on the left versus right ear, we have recently shown that hemispheric lateralization of alpha power differentially signifies auditory target selection versus distractor suppression in case one sound source is presented in the free field in front of the listener, while another sound source systematically varies between left and right. Our findings enrich the development of realistic scenarios, such as virtual reality (VR), to study auditory attention.

## Towards more realistic acoustic scenarios inside the laboratory

Goal-oriented behaviour requires selective processing of relevant information but also suppression of irrelevant, distracting input. Evidence suggests that attentional selection is neurally implemented through enhanced gain [e.g., 1] and selectivity [e.g., 2] in neural processing of the attended stimulus. However, it is less clear at present how the suppression of distracting information (i.e., "filtering") is implemented, especially in the auditory modality, where acoustic distraction is ubiquitous.

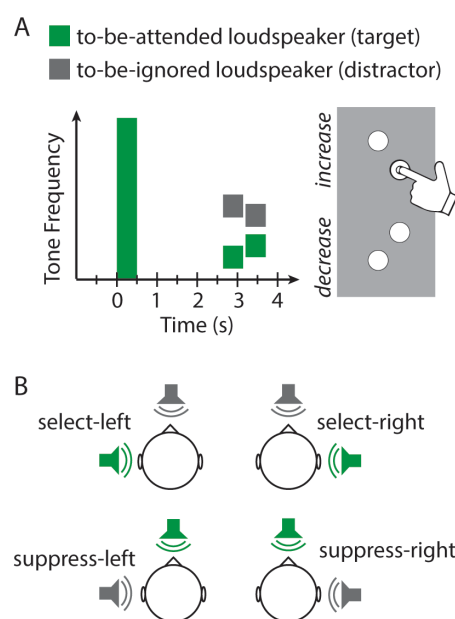
In previous spatial attention studies, spatial locations of target and distractor stimuli have often been perfectly confounded by design [e.g., 3, 4]. That is, whenever the target stimulus was presented on the left, the distractor was presented on the right, and vice versa. This made it impossible to unambiguously assign observed neural processes to either target selection or distractor suppression. In auditory studies, this created a rather artificial listening scenario with competing sound sources on the left and right side. In real-life listening scenarios, it is much more common to listen to a sound source in the front and to ignore competing sources on the left or right side.

In our research, we use electroencephalography (EEG), which is a silent brain imaging technique with a high temporal resolution. In essence, time-space summation of postsynaptic potentials from huge assemblies of cells arranged in parallel eventually results in a signal measurable

in the EEG [for a more detailed introduction to EEG in auditory neuroscience, see 5].

In a recent study [6], we decoupled the spatial arrangement of target and distractor tone sequences by keeping one of the two fixed in the front of the participant and varying the spatial position of the other between left and right. This resulted in a more ecologically valid listening situation, which allowed us to test the hypothesis that suppression of auditory distraction on the left versus right side modulates lateralized alpha power in the human EEG. Hypotheses and analyses methods were pre-registered prior to data collection (<https://osf.io/bv7zs>).

The task was adapted from Dai and colleagues [7]. On each trial, two tone sequences were presented concurrently at two different locations and were separated in their fundamental frequency (i.e., pitch). Tone sequences were presented in the periphery (i.e., free field) using a pair of loudspeakers. The location of a loudspeaker could be either front or side (i.e., 0 or ±90 degrees azimuth with no elevation, respectively; all relative to ear-nose-ear line).



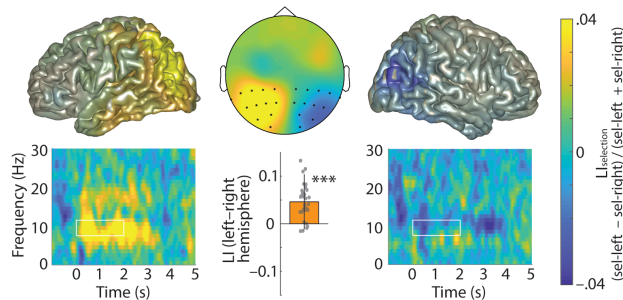
**Figure 1.** (A) Trial design. Presentation of a broad-band auditory spatial cue (1–10 kHz) was followed by two tone sequences, each consisting of two brief (0.5 s) complex tones, at different locations. Participants had to indicate whether the tone sequence at the target location increased or decreased in pitch. (B) Competing tone sequences were presented in free field in four experimental conditions. To investigate target selection, the target loudspeaker could either be left or right (with the distractor fixed in the front; top row). To investigate distractor suppression, the distractor loudspeaker could either be left or right (with the target fixed in the front; bottom row).

At the start of each trial, an auditory cue was presented on one loudspeaker to inform the participant about the target location (front, left, or right). After a jittered period of ~2 sec

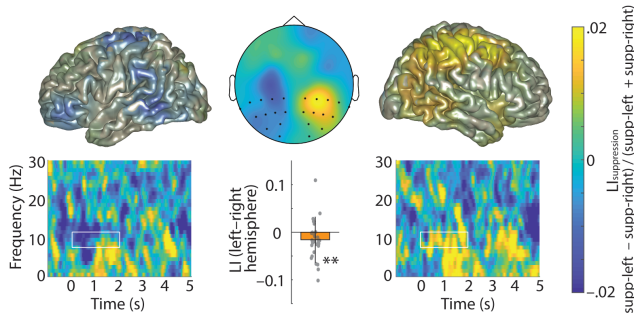
relative to cue offset, two tone sequences were presented concurrently. Participants reported whether the target tone sequence had increased or decreased in pitch. There were two response options for each possible direction (i.e., increase or decrease), indicating high/low confidence in the response (Fig. 1).

We found that selection of lateralized auditory targets under fixed distraction from the front induced pronounced hemispheric lateralization of oscillatory power in the alpha frequency band (Fig. 2A). This agrees with previous spatial attention studies that did not use distractors and found hemispheric lateralization of alpha power in response to targets on the left versus right side [e.g., 8]. Alpha power relatively increased in the hemisphere ipsilateral to the target, and decreased contralaterally. Statistical comparison of the lateralization index ( $LI_{\text{selection}}$ ) for occipito-parietal left- versus right- hemispheric electrodes was statistically significant ( $Z = 4.69$ ;  $p < 0.001$ ). EEG source reconstruction revealed strongest lateralization of alpha power for target selection in bilateral parietal and occipital cortex regions [in line with 9].

A EEG power for selection of lateralized targets (fixed distractor position)



B EEG power for suppression of lateralized distractors (fixed target position)



**Figure 2.** (A) Time-frequency representations on the left and right side show the grand-average lateralization index for selection of lateralized target stimuli ( $LI_{\text{selection}}$ ) at 11 left- and 11 right-hemispheric electrodes (highlighted in topographic map), respectively. Topographic map and brain surfaces show LI for alpha oscillatory power in the time-frequency range marked by the white outline (8–12 Hz; 0–2 s). Bar graph, error bar, and dots show average,  $\pm 1$  between-subject SEM, and single-subject differences of alpha power lateralization for left- minus right-hemispheric electrodes, respectively. (B) Same as A, but for the lateralization index for suppression of lateralized distractors ( $LI_{\text{suppression}}$ ). \*\*  $p < 0.01$ ; \*\*\*  $p < 0.001$ .

The most important objective of this study was to test whether the suppression of distractors on the left versus right side under fixed attention to the front induces lateralization of alpha power as well. This was the case (Fig. 2B). As predicted, distractor suppression modulated alpha power orthogonally to target selection: Alpha power relatively increased in the hemisphere contralateral to the distractor

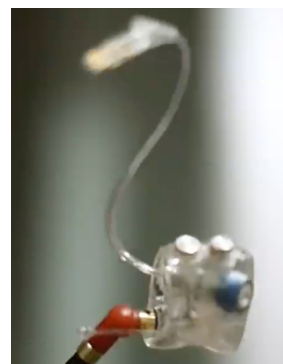
and decreased ipsilaterally. Thus, the lateralization index ( $LI_{\text{suppression}}$ ) was more negative at occipito-parietal left- versus right- hemispheric electrodes ( $Z = -2.67$ ;  $p = 0.008$ ).

These results indicate that auditory target selection and distractor suppression independently modulate lateralized alpha power, however, in opposite directions. On the one hand, these findings support so-called “active suppression” models of attention, in which suppression is not a necessary by-product of selection but an independent neuro-cognitive process. On the other hand, results demonstrate the feasibility and great potential to employ more realistic listening scenarios to study auditory attention.

## Mobile EEG recordings signify the focus of auditory attention

In recent years, we assessed the feasibility to record reliable EEG signals related to auditory attention using portable EEG systems outside conventional laboratory settings. This way, we have shown that EEG measures of neural entropy [10] and neural excitability [11] predict a listener’s behavior in an auditory pitch discrimination task.

Of great interest is the neural processing of target versus distracting speech signals, which reflects in an enhanced neural impulse response to the temporal envelope of the attended target speech signal [for review, see 5]. We have previously shown that the focus of auditory attention can not only be decoded from EEG signals recorded from a large number of scalp electrodes, but also from EEG signals recorded from few electrodes (Fig. 3) inside the ear canal [12]. This is an important technological advance, since EEG signals to reflect the focus of auditory attention could be used in the future in order to adapt the signal processing of a hearing aid in a way to optimally support the goal of the listener.



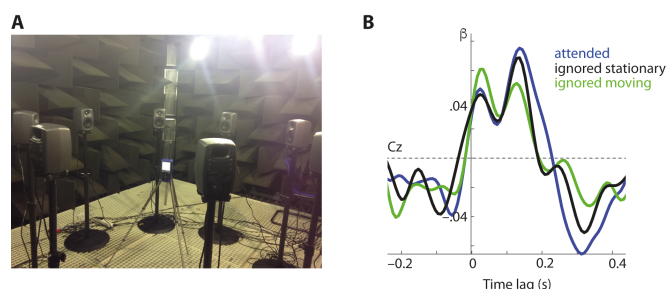
**Figure 3.** Photo of an individually fitted earpiece to record in-ear-EEG at three electrodes. Two electrodes can be seen on top of the earpiece. One additional electrode is placed on the backside. For more details, see [13].

## Auditory attention in listening scenarios containing moving sound sources

In addition to the need to develop methods to assess neural signatures of attention with portable devices (see above), it is critical to study auditory attention not only in static, but also in dynamic listening situations with moving sound sources.

In a recently started project, we presented participants with target speech at a fixed location and with competing speech distractors from moving sources, using a 360° loudspeaker array (Fig. 4). The EEG was recorded and temporal envelopes of speech stimuli were used to model neural impulse responses to the different speech signals.

Preliminary results serve as a proof of principle to demonstrate that neural impulse responses reflect a listener's focus of auditory attention in a dynamic listening scenario with moving sound sources.

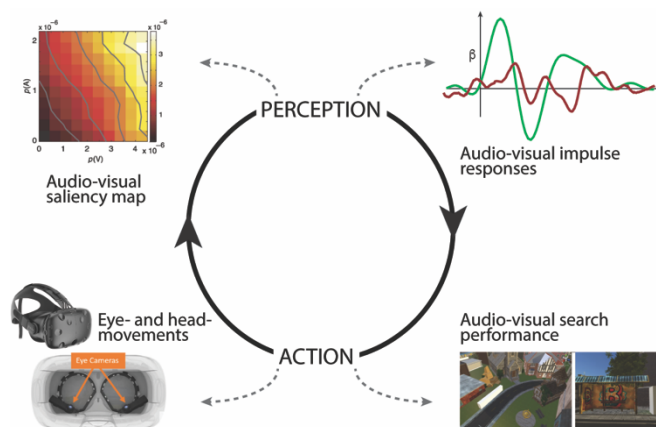


**Figure 4.** (A) In an ongoing study, we use 360° loudspeaker array, including 8 loudspeakers, to present listeners with stationary and moving sound sources to simulate dynamic real-life listening scenarios. (B) Neural impulse responses to different speech signals at electrode Cz averaged for  $N=4$  participants. The neural impulse response to attended speech was enhanced compared to stationary and, especially compared to moving speech distractors.

## Outlook: Perception-action cycles in audio-visual virtual reality (VR)

In the future, we will combine the above described advances in mobile EEG recording technologies in real-life acoustic environments and dynamic acoustic scenarios with audio-visual virtual reality (VR) and recording of eye movements as a marker of human active exploration behavior. The goal of this upcoming project is to transcend important limitations that have been inherent to human auditory research by primarily bridging the gap into state-of-the-art, interactive multi-modal virtual reality. In the visual domain, experiments utilizing virtual reality have already indicated significant differences to classical laboratory studies.

We will consider auditory scene analysis not as an isolated process, but investigate its interaction with sensory input from the visual modality, as well as human action. A first research question will be how auditory and visual information are integrated into an audio-visual saliency map? Such a saliency map predicts the spatial trajectory of human attention, which can for instance be validated by prediction of the next eye movements to a potentially relevant object in virtual reality. Next, we will study how human action (i.e. primarily head- and eye movements) impact audio-visual scene analysis. In this sense, every perception (e.g. an object of interest on the left side) induces a subsequent action (e.g. rotation of head to the left). In turn, every action immediately changes the audio-visual sensory input, which results in recurrent perception-action cycles (Fig. 5). Audio-visual virtual reality allows, at the same time, for realistic but also well-controlled audio-visual stimulus delivery.



**Figure 5.** Schematic depiction of a perception-action cycle. Perception manifests in audio-visual saliency maps (top left; [14]) and neural impulse responses to auditory and visual stimuli in the electroencephalogram (EEG; top right). Action manifests in eye- and head movements of the participant (bottom left [15]), as well as in the successful performance of solving an audio-visual search task in virtual reality (bottom right).

The overarching rationale here is that organizational principles of acoustic and auditory processing are likely to not only quantitatively, but also qualitatively change in more realistic multi-sensory environments. Notably, the integration of human audio-visual exploration and active search behavior into models of auditory perception is critical. We will characterize and model guidance of attention by behavior goals (top-down) as well as by saliency (bottom-up) in interactive audio-visual scenes.

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