Evoked responses to auditory vs. visual attentional cues in auditory spatial discrimination

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INTRODUCTION

Attention facilitates processing of objects, events, or locations in complex scenes.

Very few previous studies looked at:

– the effect of attention on sound localization,
– whether the effect is modality-dependent,
– whether there is a difference for exogenous vs endogenous attention.

Past studies found:

– cueing improves reaction times (Spence and Driver, 1994),
– small (Sach et al., 2000) or no (Kopco et al., 2001) improvements in localization accuracy,
– enhancement of auditory discrimination based on ILD or ITD when the listener's gaze was directed to stimulus, but not when cue was auditory (Maddox et al., 2014).
– lateralized sound elicited an enlarged contralateral positive potential in the interval of 200–450 ms after sound onset localized in visual cortex. This auditory evoked contralateral occipital positivity (ACOP) reflects the orienting of attention toward the cued location, which improves perceptual discriminations at that location (McDonald et al., 2013)

Kopco et al. (2018):

– examined the effect of exogenous attention on spatial discrimination for visual vs auditory cues, with gaze fixed at a neutral location, using a fully simulated virtual auditory environment,
– also measured EEG to examine neural correlates of attentional control,
- analysis of target-related effects (summarized in Figs. 3 and 4) showed that discrimination can be affected by automatic attentional cuing, not only by gaze direction (as in Madox et al, 2014),
- cuing effect depended on modality and validity of the cue, mainly due to detrimental effect of auditory invalid cues (Fig. 3),
- ERPs 200-300ms after target onset corresponded with the behavioral effects (Fig. 4).

CURRENT STUDY

Analyze the auditory cue-evoked ERPs from the Kopco et al. (2018) study and compare them with behavioral responses. Examine the following hypotheses (based on Feng et al, 2014):

1. Early responses to auditory cue (N1 component)
– will not be predictive of validity/correctness of following target responses,
– will be larger over the hemisphere contralateral to the sound location for lateral cues re. central cues.
2. Late responses to auditory cue (ACOP)
– will be predictive of target discrimination accuracy on valid trials. There will be significant contralateral vs ipsilateral amplitude difference at occipital sites over the time window 300–400 ms for valid-correct trials, but not for valid-incorrect trials.
3. Contra-vs-ipsi amplitude difference at occipital sites will be predictive of individual differences in subjects' ability to benefit from a valid vs. invalid cue (auditory and/or visual).

METHODS

SUBJECTS, STIMULI AND SETUP

- 14 subjects (9 male)
- 2 sessions + initial practice
- 1 **session** divided into 20 blocks of 40 trials (Fig. 2), each block with fixed Fixation point (FP; +12.5° or -12.5°) and cue modality, and varying target location, target shift direction (left vs. right), and cue validity.

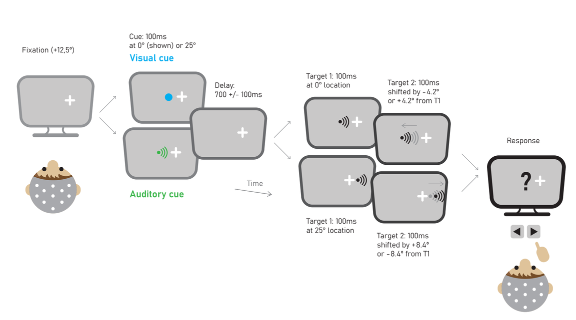

Fig. 2 Experimental setup. Temporal structure of a single trial with fixation at +12°. In a half of blocks, the trials were mirror-flipped, with fixation at -12.5° and stimuli presented in the left hemifield.

- **Target:** two 100–ms 170–Hz click trains (T1, T2), presented without a gap in a sequence [T1@0°, T2@0°±4.2°] or [T1@25°, T2@25°±8.4°], i.e., such that T2 moved to the left or right from T1. When FP was at -12.5°, T1 and T2 were at/around -25° and 0°.
- **Cue:** auditory (identical to T1) or visual (100–ms white dot), valid (same location as T1), or invalid (location 2*(FP-T1), i.e., on the other side of FP re. T1), cue validity 50%.
- **Task:** "Discriminate whether T2 was to the left or to the right of T1. Cue will be presented from the same location as target, or from a different one."
- Auditory stimuli simulated using non–individualized HRTFs and ER1 headphones.
- Visual stimuli presented on computer screen (head fixed at a constant distance from screen).
- Auditory and visual stimuli presented through DataPixx system and a computer screen.
- Responses on computer keyboard.
- ERPs recorded during sessions using 32–channel Biosemi ActiveTwo system at 4096 Hz
- EOGs recorded for eye–tracking.

BEHAVIORAL RESPONSES AND ERPS ELICITED BY TARGET SOUNDS (KOPCO ET AL., 2018)

BEHAVIORAL DISCRIMINATION PERFORMANCE (Fig. 3)

Overall visual cue performance better than auditory cue performance. Validity of cue has:
– little impact for visual cue (n.s.),
– large impact for auditory cue: invalid cue acts as a distractor (valid cue has a small effect re. visual).
- pattern similar for central (0°) and peripheral (25°) targets (symbols).

ERPS TO TARGETS (Fig. 4)

Early components (N1):
– auditory cue validity modulates target N1: N1 smaller for valid cue,
– visual cue does not modulate N1,
– target N1 after visual cue much larger than after auditory.
Later components:
– no effect of visual cue,
– auditory cue ERPs differs 200-300ms post-T1 (100-200ms post-T2)

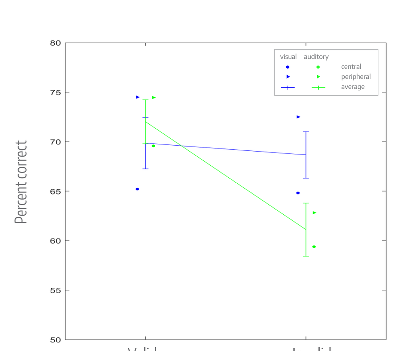

Fig. 3 Percent correct responses as a function of cue validity plotted separately for the visual and auditory cues, (A). Symbols represent different target locations.

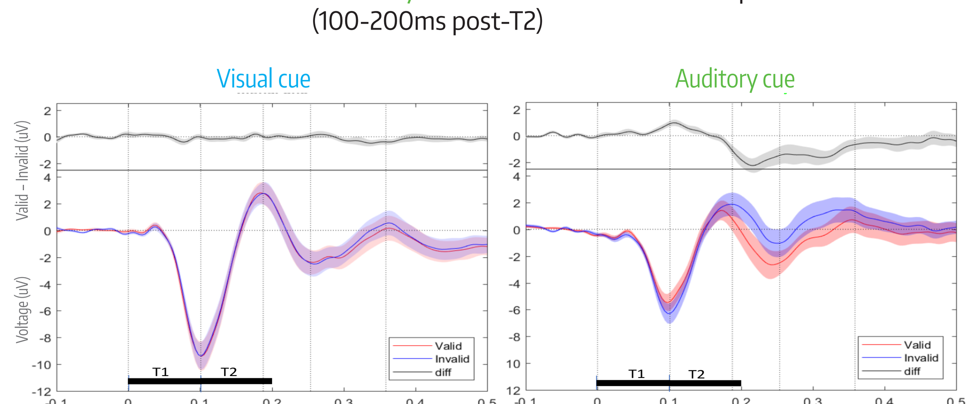

Fig. 4 ERP responses to targets averaged across electrodes Cz, Fc1, Fc2, Fz. Vertical dotted lines indicate onsets of the target stimuli T1 and T2, and of ERP components P1, N1, P2.

Visual cue has very small effect. Invalid auditory cue acts as distractor. N1 modulation likely a result of spatially-specific adaptation, not attention. Later components likely a correlate of behavioral interaction of cue modality x validity for auditory cue.

RESULTS

ERPS ELICITED BY CUE SOUNDS

EARLY COMPONENTS (N1)

Fronto–temporal N1 amplitude over 90–150ms was larger over the hemisphere contralateral to the sound location ($F(1,12)= 6.798$, $p = 0.023$); and larger for peripheral cue than for central cue ($F(1,12)= 7.325$, $p = 0.019$) (Figure 5A). Also, Hemispheric Laterality x Cue Position interaction was found to be highly significant ($F(1,12) = 9.508$, $p= 0.009$). Specific comparison showed that this interaction was the result of the N1 difference between peripheral and central cue being larger in hemisphere contralateral than ipsilateral to fixation (Figure 5b).

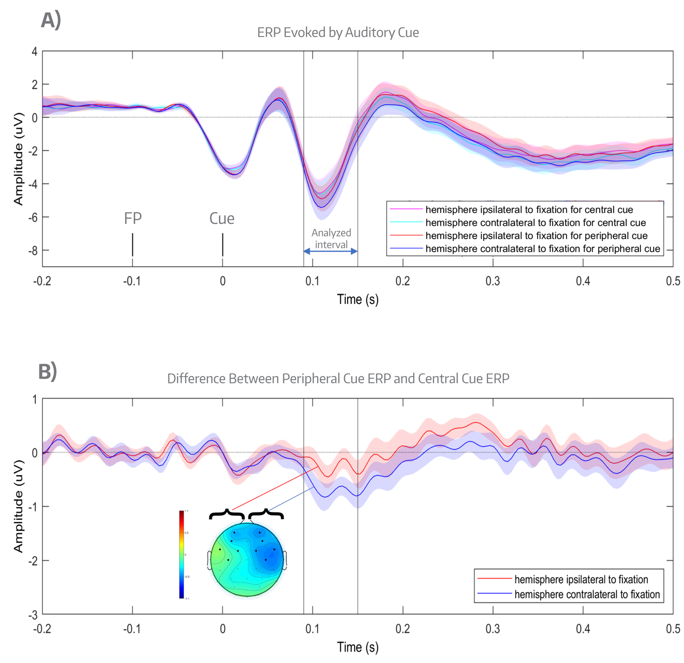

Fig. 5

A) ERP waveforms elicited by peripheral and central cue sounds averaged over five pairs of fronto–temporal electrodes ipsilateral and contralateral to fixation (note that peripheral cue was always on the same side as fixation). Onsets of FP, cue, and the analyzed interval are marked on X-axis.

B) Difference between peripheral and central cue ERPs from panel A, separately for the two hemispheres. The inset shows topographical distributions of differences between lateral and central cue responses over the analyzed interval. Electrodes considered in this analysis are indicated by large dots.

For N1 component there is difference between central and peripheral auditory cue position as a result of early sensory processing. The difference is more pronounced in hemisphere contralateral to fixation, likely encoding the horizontal sound location.

LATE COMPONENTS (ACOP)

Later components were examined in two 300-ms time windows (100-400 ms and 400-700 ms) over occipital electrodes for which ACOP response was previously reported (300-400 ms post-cue) for valid correct (and all invalid) trials but not for valid incorrect trials. Here, the comparison between correct and incorrect responses could not be done directly due to low number of valid auditory-cue trials with incorrect responses (especially for peripheral cue, Fig. 3). Instead, analyses were performed on correct and incorrect data combined, split only by validity, with the assumption that any observed effects of validity are driven by the difference between valid correct and incorrect trials. Also, correct-only data are shown for comparison.

Fig. 7 shows temporal profile of responses of the occipital electrodes for each brain hemisphere and cue location, as well as the hemisphere differences:
– no effects of cue in the interval 100 – 400 ms, including
– no effect in the ACOP interval of 300 – 400 ms.
– in the interval of 400 – 700 ms, contralateral negativity is observed for invalid peripheral cues, but not for valid peripheral or any central cues (ANOVA interaction of hemisphere X cue validity X cue location: $F_{1,13}= 5.281$, $p = 0.039$).

Fig. 8 shows the 400 – 700 ms data from Fig. 7 averaged across time, both when correct and incorrect trials are combined (like in Fig. 7) and when only correct trials are considered:
– there is a slight (non-significant) contralateral positivity for invalid peripheral-cue trials, consistent with ACOP,
– the contralateral negativity for invalid central trials is the main effect, also preserved when only correct trials are considered.

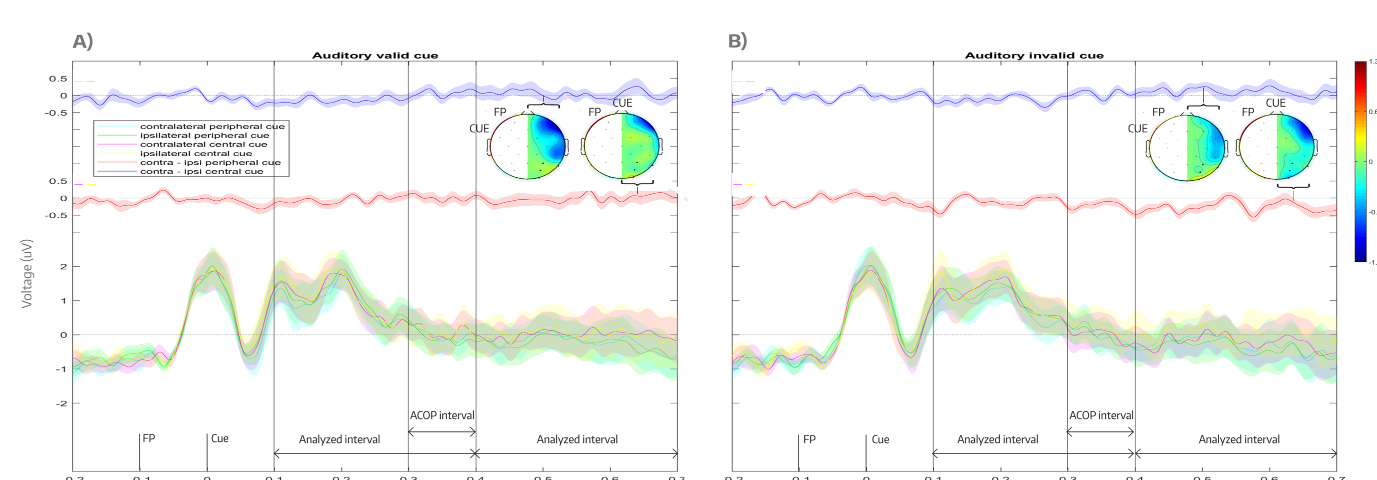

Fig. 7 Late components of ERPs over occipital electrodes. The main traces (lower section of each panel) show the across-subject ERP mean (+/-SEM) for all combinations of cue positions (peripheral vs. central) and brain hemispheres (contralateral vs. ipsilateral to the fixation point), plotted separately for valid (A) or invalid (B) trials independent of the response correctness. Traces in the upper section show the hemispheric difference (contra – ipsi) separately for the peripheral and central cues, based on the corresponding traces in the lower section. Insets show the topography of the contra – ipsi differences, as well as the locations of the CUE and the FP. Baseline for each trace was computed over the interval of -200 to 0 ms re. cue, thus including a part of the response to the FP.

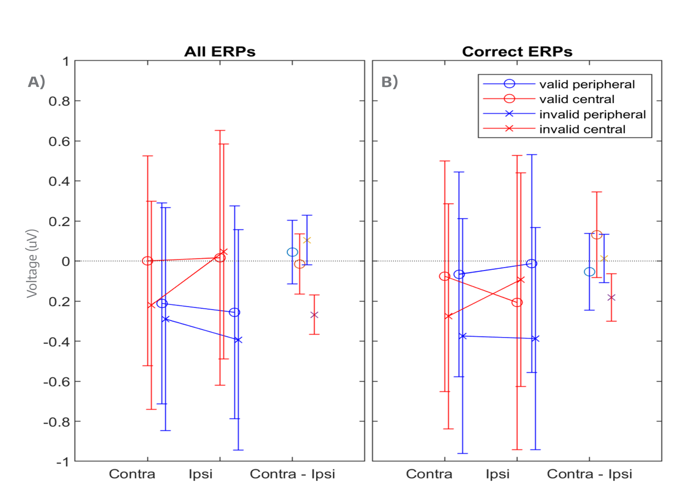

Fig. 8 A) ERPs over the occipital electrodes from Fig. 7 averaged across the 400 -700ms time window (+/- SEM) for data pooled across the correct and incorrect trials. B) the same graphs as in panel A across for data pooled across correct trials only (B).

A new attentional auditory cue-evoked contralateral occipital negativity was observed in this study. It is likely related to the previously reported auditory-evoked contralateral occipital positivity (ACOP). However, the new contralateral negativity was observed only for central cues (ACOP was previously reported for peripheral cues) over time window of 400 – 700 ms (ACOP 300 – 400 ms) and for the valid vs. invalid contrast (ACOP was observed mainly for valid correct vs. incorrect). Importantly, it is possible that the observed difference in validity is driven by the same difference in validity/correctness as observed in ACOP (Feng et al., 2014) where, averaged across correctness, the effect would also produce a validity-dependent difference.

CORRELATIONS BETWEEN LATE ERPS AND BEHAVIORAL PERFORMANCE

To further examine the link between validity/correctness of behavioral responses and the cue-evoked late occipital ERPs, we computed the correlations between individual subjects' percent correct discrimination responses and the hemispheric difference in the 400-700-ms occipital ERPs (Figs. 9 and 10):

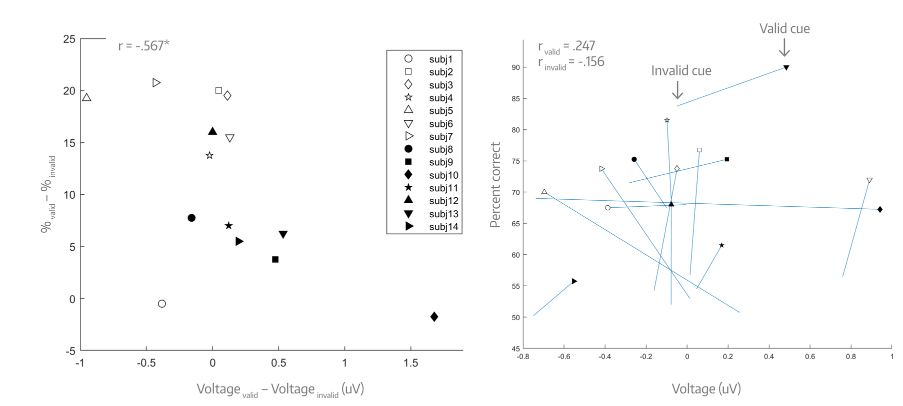

Fig. 9 Individual subjects' behavioral discrimination response accuracy as a function of the late (400 – 700 ms) occipital ERP hemispheric differences for auditory cue conditions, combined across the cue locations. A) Difference valid and invalid cue conditions. B) Correlation plotted separately for the valid cue condition (symbols) and invalid cue conditions (for each subject the endpoint of the line without a symbol). Pearson's correlation coefficients for all data are shown within each scatterplot. Levels of significance: $^*p < 0.05$.

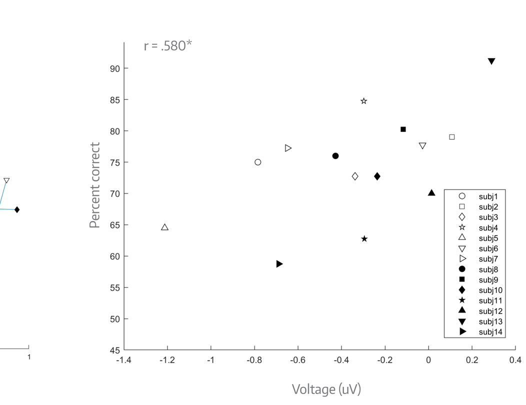

Fig. 10 Individual subjects' behavioral discrimination response accuracy as a function of the late (400 – 700 ms) occipital ERP hemispheric differences for valid peripheral cues, combined across visual and auditory cue modality. Pearson's correlation coefficient is also shown. Levels of significance: $^*p < 0.05$.

– For the valid-invalid contrast for the central auditory cue, the correlation was negative, but not significant: $r(14) = -.494$, $p=0.073$.
– For the valid-invalid contrast and data pooled across both auditory cue locations, a significant negative correlation was observed: $r(14) = -.567$, $p=0.035$ (while for the peripheral cue alone it was, again, not significant). Fig. 9 shows the correlation (left-hand panel) as well as the data plotted separately for the valid and invalid conditions (right-hand panel), for which it was not significant.
– In addition, for the valid peripheral cue and data combined across auditory and visual cue modalities, a significant positive correlation was observed $r(14) = .580$, $p=0.03$ (Fig. 10). This correlation was mostly driven by the visual-cue data which approached significance even without considering the auditory data ($r(14) = .493$, $p=0.073$).

Supporting the validity/correctness analysis above, correlation analysis found that the size of auditory cue–elicited late occipital ERP hemispheric difference predicts the size of the benefit of valid cues for individual subjects (mostly driven by central cues). In addition, the same ERP response for the valid peripheral cue was positively correlated with discrimination accuracy (mostly driven by visual cue data).

CONCLUSIONS

Stimulus-driven automatic spatial attention influences auditory spatial discrimination:
Valid and invalid visual cue results are similar ⟶ the cuing effect is small. Valid auditory cue performance is similar to visual cue performance. The main effect is degradation of performance by invalid auditory cue. The distracting effect of invalid auditory cue is possibly related to the fact that it was identical to the target. These effects correlate well with P2-N2 ERP components 200-300 ms post-target onset) over frontal electrodes.

Early-component (N1) frontal ERPs to auditory cues are:

– larger over the hemisphere contralateral to the sound location,
– larger for peripheral cues, such that difference between peripheral and central cue is more pronounced on contralateral side. These responses are likely indicators of **sensory spatial encoding of auditory locations**.

Late-component occipital ERPs to auditory cues are:

– not correlated with validity/correctness of discrimination responses in time window 300-400 ms, as reported previously by ACOP response,
– correlated negatively with validity/correctness of discrimination responses for central cue location in time window 400-700 ms. We observed **auditory cue–evoked contralateral occipital negativity** that is likely to indicate automatic attentional modulation of target processing by the preceding auditory cue.

Late-component occipital ERPs to peripheral visual (and auditory) cues also correlate with discrimination responses across subjects, supporting the hypothesis that these late occipital responses are indicators of automatic attentional modulation.

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