ERP signatures of auditory awareness in cross-modal distractor-induced deafness

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Abstract

Previous research showed that dual-task processes such as the attentional blink are not always transferable from unimodal to cross-modal settings. This study investigated whether such a transfer can be stated for a distractor-induced impairment of target detection established in vision (distractor-induced blindness, DIB) and recently observed in the auditory modality (distractor-induced deafness, DID). A cross-modal DID effect was confirmed: The detection of an auditory target indicated by a visual cue was impaired if multiple auditory distractors preceded the target. Event-related potentials (ERPs) were used to identify psychophysiological correlates of target detection. A frontal negativity about 200 ms succeeded by a sustained, widespread negativity was associated with auditory target awareness. In contrast to unimodal findings, P3 amplitude was not enhanced for hits. The results support the notion that early frontal attentional processes are linked to auditory awareness, whereas the P3 does not seem to be a reliable indicator of target access.

Keywords: cross-modal perception; distractor-induced deafness; auditory awareness negativity; P3; event-related potentials

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1. Introduction

The successful detection of a stimulus depends on several prerequisites. Some are defined by the properties of the stimulus itself, such as its salience (Itti, 2005; Nothdurft, 1993), others by the state of the observer, such as available attentional resources (Cohen & Chun, 2017). The state of the observer can be affected by physical events preceding the onset of a target (Folk & Remington, 1998; Kamke & Harris, 2014; Niedeggen et al., 2012). Stimuli preceding the target can sensitize the system and ease detection (i.e. priming/cueing effects, for an overview: (Schacter & Buckner, 1998)). However, preceding stimuli can also reduce the detectability of the target or prevent detection entirely (i.e. forward masking, (Enns & Di Lollo, 2000)). In the current study, we take advantage of an experimental paradigm manipulating the occurrence of pre-target events to reduce target detection, the distractor-induced deafness (DID, (Kern & Niedeggen, 2021)).

The DID is related to the established *distractor-induced blindness* (DIB, (Michael et al., 2011; Sahraie et al., 2001)). In both paradigms, two rapid streams of stimuli are presented concurrently. Each stream contains one task-relevant stimulus: one is defined as a target (i.e. the onset of a short coherent motion in a random dot kinematogram, or the increase in loudness in a continuous tone) and is embedded in stream 1, the other as cue (i.e. single event of red fixation, or a deviant tone) in stream 2. The subject's task is to decide whether a target has been presented simultaneously with or following the onset of the cue.

Given a sufficient salience of cue and target, participants can detect the relevant stimuli reliably. However, if stimuli sharing the target's properties are presented in the target stream before cue onset, detectability of the target is significantly impaired (Hesselmann et al., 2006; Kern & Niedeggen, 2021; Sahraie et al., 2001). In the following, we will refer to these pre-target events as 'distractors'. Importantly, and in striking contrast to *contingent attentional capture* (Folk et al., 1992), neither distractor-induced blindness nor distractor-induced deafness can be evoked by a single distractor presented in temporal proximity to the target. In both modalities, the presentation of multiple distractor episodes is necessary to

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affect target detection (Hesselmann et al., 2006; Winther & Niedeggen, 2017b). Systematic variation of the cue-target interval also revealed a difference to the *attentional blink* (AB, (Raymond et al., 1992; Shapiro et al., 1997)): In contrast to the AB, target detection is most impaired if cue and target are presented simultaneously and gradually recovers after 200 to 300 ms (Niedeggen et al., 2002; Sahraie et al., 2001; Winther & Niedeggen, 2017a).

Supported by electrophysiological data (Niedeggen et al., 2015; Niedeggen et al., 2004; Niedeggen et al., 2012), it has been suggested that distractors gradually activate a negative attentional set. Since distractors share the target's features, the activation of this inhibitory set reduces the probability that the target event is represented in working memory and is thus reportable.

The following characteristics have been observed for both DIB and DID and therefore within visual and auditory modality: (1) the presentation of multiple distractors reduces probability of target detection. (2) The strongest impairment of target detection occurs if cue and target are presented at a stimulus onset asynchrony (SOA) of 0 ms. (3) The processing of the cue-target complex elicits a prominent P3 component, whose amplitude is enhanced if the target can be reported (Niedeggen et al., 2015; Niedeggen et al., 2002). This late event-related potential (ERP) effect was recently replicated in the auditory domain (Kern & Niedeggen, 2021). The observed reduction of P3 amplitude for missed targets has been attributed to a temporary deficit in a post-perceptual updating process in working memory (Niedeggen et al., 2015; Sergent et al., 2005). (4) Previous studies did not find evidence that the failure to detect a target stimulus is associated with a suppression of early sensory processing (Kern & Niedeggen, 2021; Niedeggen et al., 2002).

However, ERP studies also indicated a difference in target processing between the visual and auditory domain. In contrast to the visual modality, where detected and missed targets differed solely with regard to P3, distractor-induced deafness was additionally characterized by a frontal negativity around 200 ms. This negativity – preceding the P3 – was more expressed if the auditory target was correctly reported. The topography of the frontal

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negativity did not share the characteristics of a sensory evoked potential. Therefore, we tentatively suggested that this ERP effect can be related to a processing negativity (Näätänen et al., 2011) mirroring an allocation of attention to the target (Kern & Niedeggen, 2021).

In sum, the aforementioned studies indicate that distractor effects can be triggered by visual and auditory stimuli. In both modalities, multiple distractor epochs that share the target's features are necessary to elicit a target detection deficit. The functional processes underlying access to the target may differ between modalities. In this study, previous within-modality approaches were extended: using a cross-modal design, we tested whether the auditory DID effect can be replicated if the cue is defined in a visual stream. Moreover, it was examined whether the distinct ERP signature of auditory target access can be observed in the cross-modal setting.

Cross-modal studies can answer the question whether attentional resources are shared across modalities, or if distinct resources are recruited. If processing limitations observed in unimodal settings are consistently expressed in cross-modal tasks, the former model can be favored.

Evidence for shared resources has been found in some cross-modal studies, which defined an auditory and a visual target (Dux et al., 2006; Sigman & Dehaene, 2006). Moreover, it has been observed that target processing can be affected by a distractor event occurring in a second modality (Driver & Spence, 1998; Kamke & Harris, 2014; Turatto et al., 2002). However, other findings suggested an important role of modality-specific attentional resources for visual and auditory modality (Keitel et al., 2013; Larsen et al., 2003; Porcu et al., 2014; Talsma et al., 2006). It has been put forward that the recruitment of shared or distinct attentional resources depends on the presence of speeded response instructions, and on whether object-based or visuo-spatial attention is required (Alais et al., 2010; Wahn & König, 2017).

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The inconsistency concerning cross-modal effects also becomes evident in the attentional blink. This deficit in reporting a second target, if it is presented shortly after a first target, has been reliably observed in unimodal presentation mode (visual: for a review (Dux & Marois, 2009; Martens & Wyble, 2010), auditory: (Shen & Alain, 2010; Tremblay et al., 2005)). Nevertheless, the replicability of the effect in a cross-modal setting has been disputed: While some behavioral studies found an audiovisual AB (Arnell & Jenkins, 2004; Arnell & Jolicoeur, 1999; Arnell & Larson, 2002; Jolicoeur, 1999), others did not (Duncan et al., 1997; Hein et al., 2006; Potter et al., 1998; Soto-Faraco & Spence, 2002; Van der Burg et al., 2007).

A psychophysiological approach to test the deployment of attentional resources is the recording of event-related potentials (ERPs). Unimodal visual and auditory AB studies revealed a modulation of the centro-parietal P3 within the typical AB window (Dell'Acqua et al., 2015; Sergent et al., 2005; Shen & Alain, 2010; Vogel & Luck, 2002). Cross-modal AB studies found a corresponding reduction – or temporal delay – of the P3 in response to the second target (T2) at short T1-T2 lags (Arnell, 2006; Dell'Acqua et al., 2003; Ptito et al., 2008). Importantly, the cross-modal P3 effect was not necessarily related to the participant's report: it was observed in the presence ((Dell'Acqua et al., 2003); (Arnell, 2006), Exp. 3), but also in the absence of a behavioral AB effect ((Arnell, 2006), Exp. 4; (Ptito et al., 2008), but see (Finoia et al., 2015) for contrasting results). To our knowledge, to date no cross-modal ERP study on the AB directly compared detected and missed target processing.

To sum up, previous cross-modal research revealed that unimodal effects do not automatically translate to cross-modal stimuli. This led to the question whether a distractor-induced deafness can be elicited in a cross-modal setting. Our hypotheses are based on the assumption that an inhibitory process is triggered by distractors irrespective of the modality of the cue, and that consequently an auditory target detection deficit (i.e. DID) is also expected if a visual cue is provided. This assumption is in line with previous results indicating

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that the formation of a modality-specific task set leads to an orientation of attention to the distractor's modality, if the target is expected to appear in this modality (Grant et al., 2020).

More explicitly, we stated the following two hypotheses, which were examined in a behavioral and a subsequent ERP study:

- 1) On a behavioral level, multiple target-like distractors were expected to impair target detection and lead to decreased detection rates compared to zero and one distractor conditions, in line with previous unimodal research (Kern & Niedeggen, 2021).

Independent of the cue being defined in the visual domain, the repeated presentation of auditory distractors in the pre-cue epoch was expected to trigger the formation of a negative attentional set. This cumulative inhibition of target features elicited by multiple distractors sharing these features should affect the detectability of the upcoming auditory target.

- 2) Given that the distractor-induced target detection impairment can be identified in a cross-modal setting, a replication of the two ERP signatures of target access observed in our auditory DID study was expected. First, we anticipated an enhanced frontal negativity (FN) for detected compared to missed targets around 200 ms, as reported in previous auditory studies (Eklund & Wiens, 2019; Kern & Niedeggen, 2021), if it is a reliable signature of auditory awareness. Second, successful target detection was assumed to be accompanied by a larger late positivity (P3) around 500 ms compared to misses, which has been related to working memory updating.

2. Methods

Data, stimuli and PsychoPy code are provided in an open repository.

2.1 Participants

Sample sizes were computed a priori using G*Power (Faul et al., 2007) for $\alpha = .05$ and an intended power of 80% to detect effects in a F-Test with repeated measurement. For the

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behavioral study, we conservatively assumed a medium sized effect ($f=.30$) for the within-subject factor 'number of distractors' (one vs. multiple distractors), leading to a calculated sample size of $N=24$. For the ERP study, we expected a medium to large effect of $f=.35$ for the frontal negativity and P3, based on the effects observed in the auditory DID study (Kern & Niedeggen, 2021). This resulted in a calculated sample size of $N=19$ for the difference between hits and misses (within-subject factor 'condition').

Twenty-one participants took part in the behavioral study, and thirty-eight new participants were recruited for the ERP study. Samples of both studies included healthy volunteers with no history of psychiatric or neurological disorders, normal or corrected-to-normal vision and reported normal hearing ability. Participants were recruited in the university environment and via an advertisement on social media and either received course credit or a compensation of 10 €/hour. All participants gave written informed consent prior to the experiment. The experimental procedure was approved by the ethics committee of Freie Universität Berlin (027/2019).

Exclusion criteria were based on the previous auditory DID study (Kern & Niedeggen, 2021): (1) unreliable target detection in the pretest (target detection in less than 60% of pretest trials), and (2) unreliable target detection in the experiment (less than 25% correct target detection in the zero distractor condition). For the behavioral study, the final sample consisted of 20 participants (13 women; 18 — 39 years of age; M_{age} : 29.20, SD: 5.92). The excluded participant did not fulfill the first criterion.

For ERP analysis comparing hits and misses a third exclusion criterion applied, in line with the auditory DID study: participants with a high number of EOG/EEG artefacts (eye blinks/movements, movement artefacts, or high EEG alpha activity ($>80 \mu V$)), resulting in unreliable averaged ERP signals (less than 10 valid trials) were excluded. Due to this exclusion criterion, three participants in the ERP study had to be discarded due to a high number of EEG artifacts, and one participant did not complete the experiment and was thus excluded. Of the remaining 34 participants, 21 showed a sufficient number of misses (≥ 10

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valid miss trials ($\geq 12.5\%$ of trials in multiple distractor condition)) for the contrastive analysis between hits and misses (12 women; 19 — 34 years of age; M_{age} : 25.29, SD: 4.84). In the following, we will refer to these participants as “distractor-sensitive” subgroup. Thirteen participants showed less than 10 misses (9 women; 19 — 33 years of age; M_{age} : 23.31, SD: 5.20). Consequently, the data of these “distractor-insensitive” participants could not be considered for the comparison of hit- and miss-associated ERPs but were included in additional analyses.

2.2 Stimuli, procedure, and design

The experimental procedure and auditory stimuli were adapted from the auditory DID experiment (Kern & Niedeggen, 2021) to ensure comparability of results between both studies. The experiments were presented using a PsychoPy protocol (Python version 3.7.6) on a Windows-running PC and took place in a sound-attenuated chamber with dimmed indirect lightning. The current behavioral and ERP study had an identical set-up, except for a few differences described at the end of this section.

Two rapid serial auditory presentations (RSAPs) were played simultaneously via headphones (Sennheiser OCX 686i, Wedemark-Wennebostel, Germany). The auditory stimuli and sequences were created and edited with the programs “Tone Generator” and “WavePad Editor” (NCH Software, Greenwood, USA). The first RSAP stream consisted of a continuous tone, which had a reduced amplitude (-20 dB) compared to the other sequence. The continuous tone showed a modulation at 5 Hz in a frequency range from 270 – 330 Hz. Distractor and target events could appear in stream 1 and were characterized by an increase in amplitude (+10 dB) for 100 ms. The second RSAP stream consisted of 50 pure sine-wave tones with 30 ms presentation time and 70 ms inter-stimulus interval. The tones were randomly selected from a set of seven tones in the frequency range of 1,800 – 2,200 Hz. The participants heard stream 1 on the right ear, and stream 2 on the left ear. Both streams started concurrently without jittering. The same setup was used in the previous experiment establishing the auditory DID, except for an auditory cue being defined in the second stream.

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In the current study, the second stream did not contain a cue and was therefore not task relevant. To allow a comparison between the previous auditory and the current cross-modal study, stream 2 was kept in the cross-modal experiments, since it might have triggered an EEG rhythm in the previous study.

The cue was defined in the visual modality. In addition to the relevant RSAP stream, participants were instructed to monitor a concurrent RSVP stream consisting of eight bars arranged in a circle. Comparable to a visual cue signaling a loading process ('preloader' symbol), the impression of a clockwise radial motion was generated by varying the luminance of adjacent bars. Changes in luminance were synchronized with the presentation rate in both auditory RSAP streams and appeared each 100 ms. The cue event was defined by the onset of a small circle with black outline (0.186° in diameter) presented for 100 ms at the position of the missing bar of the preloader symbol (see Figure 1). The visual stream was presented on a 20" monitor (Sony Trinitron Multiscan G520). Viewing distance was fixed at 62 cm with the head stabilized on a chin rest, resulting in a retinal size of 1.66° (in diameter) of the preloader symbol.

Each combined RSVP/RSAP sequence had a duration of 5,000 ms. The cue was presented at a randomized temporal position between 3,100 – 4,000 ms after trial onset. An increase in the amplitude of the continuous tone occurring with – or following – the cue was defined as target. Task-irrelevant distractors were defined as increases in amplitude preceding cue onset. The SOA between the final distractor in the pre-cue epoch and cue onset was at least 500 ms to avoid a superimposition of ERP responses. Distractors could occur at random positions within the pre-cue epoch with a minimum SOA of 200 ms and a maximum SOA of 700 ms between distractors. Figure 1 illustrates the trial design.

Figure 1

Experimental design of both cross-modal experiments.

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Note. Participants heard a continuous tone on the right ear (270 - 330 Hz), which could contain the target stimulus. On the left ear, a sequence of pure tones (1,800 - 2,200 Hz) was presented simultaneously. This second stream was not task relevant and is therefore not depicted above. Simultaneous to the auditory streams, a RSVP containing a 'preloader' symbol was presented on the screen in front of the participant. The preloader symbol changed at a rate of 100 ms per frame, creating the impression of a clockwise motion. A small white circle (cue) could appear as a singular event, positioned randomly at the place of one of the 8 bars. A short increase (100 ms duration) in amplitude in the continuous tone was defined as target, but only if it was accompanied by the white circle. In the behavioral study, the cue could also precede the target. Increases in amplitude occurring before the cue were defined as distractors and should be ignored.

The participant's task was to decide after each trial whether the auditory target was presented simultaneously to or following the onset of the visual cue. Responses were given via button press on the keyboard following a corresponding question presented on the computer screen after the offset of the RSAP/RSVP sequences. Subjects were successively asked whether they observed a cue (question 1: "Did you see a small white circle?") and whether a target was detected (question 2: "Did you hear a change in the continuous tone simultaneous to (or after) the appearance of a small white circle?"). As in previous DIB/DID studies, the required verbal report was bimodal (yes/no). Response time was not limited and

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participants were instructed to respond as accurately as possible. The delayed responses ensured that ERPs were primarily related to the processing of the cue/target complex, and not affected by the preparation of a motor response.

Both behavioral and ERP study started with 32 pretest trials to ensure familiarization with the task, stimuli and response format. During this training phase, the experimenter provided verbal feedback about the correctness of the given responses after each trial. Only if the participant succeeded in detecting the target in at least 60 % of pretest trials, they were included in the main experiment (see exclusion criterion 1 in section 2.1).

In the behavioral study, the cross-modal DID effect was examined using a two-factorial design: The first within-subject factor was defined by cue-target SOAs (0 ms vs. 100 ms vs. 300 ms) and the second within-subject factor by the number of distractors preceding the cue (0 vs. 1 vs. 6-8 distractor episodes). For each of the three SOA conditions 80 trials were presented, which all contained cue and target. Within each SOA condition, 40 trials included multiple distractors, 20 trials one distractor, and 20 trials no distractors. As control condition, 30 trials contained the cue only (15 trials with multiple distractors, 15 trials without distractor). These trials allowed for an assessment of response tendencies by measuring falsely reported targets after a correctly detected cue (i.e. false alarms). Twenty additional control trials comprised neither cue nor target (10 trials with multiple distractor, 10 trials without distractors). 290 trials were presented in total. Trial order was randomized for each participant.

The ERP study focused solely on a cue-target SOA of 0 ms for which the largest cross-modal DID effect was expected. The experimental within-subject factor was defined by the number of distractors (0 vs. 1 vs. 6-8). Multiple distractors preceded cue and target in 80 trials, a single distractor in 30 trials and in another 30 trials no distractor was present. In addition to these 140 trials containing cue and target, the remaining 100 trials belonged to control conditions. In 70 trials, the susceptibility to false alarms was tested by presenting the cue only (40 trials with multiple distractors, 15 trials with one distractor, and 15 trials without

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distractor). In 30 trials, neither cue nor target appeared (10 trials with multiple distractor, 10 trials with one distractor, and 10 trials without distractor).). 240 trials were presented in total. The order of experimental conditions was randomized for each participant.

2.3 EEG recordings and analysis

An elastic cap (EASYCAP, Herrsching-Breitbrunn, Germany) with predefined electrode positions according to the 10-20-system (Jasper, 1958) was placed on the participant's head. Twenty-eight active Ag/AgCl electrodes were referenced to linked earlobes and the ground electrode was positioned at position FCz. Impedance at all electrodes was kept below 10 k Ω . Vertical and horizontal eye movements were assessed by electrodes at the outer canthi (hEOG) and at the sub- and supraorbital ridges of the right eye (vEOG). EEG signals were recorded using a 40-channel NuAmps amplifier (Software Acquire, Neuroscan Labs, Neurosoft Inc., El Paso, TX, USA). Data were band-pass filtered online at 0.1 – 200 Hz and sampled at 500 Hz. The resulting data were analyzed offline using "BrainVision Analyzer" software (Version 2.1, Brain Products GmbH, Gilching, Germany).

EEG data were segmented into 900 ms epochs (-100 to 800 ms epoch length) based on one marker, which referred to cue onset. The segments were then filtered (0.6 – 30 Hz, 50 Hz Notch) and baseline corrected (-100 to 0 ms). In a semi-automatic artefact rejection procedure, single EEG sweeps that contained ocular or muscular artefacts, slow drifts due to movements, or strong EEG alpha activity ($> 80 \mu\text{V}$) were identified and excluded from further analysis (7.27 % of trials). ERP analysis was focused on trials in which the simultaneous presentation of cue and target was preceded by multiple distractors, since the experimental question focused on the brains' state associated with target access. Depending on participant's response to the target ('hit' or 'miss'), data were averaged separately for each electrode position. If one of the averages for hits or misses comprised less than 10 trials after artifact rejection, the participant was excluded from analysis (see exclusion criterion 3). In order to estimate the separate processes triggered by cue and target processing, ERPs were also averaged for the control condition 'cue only, multiple distractors'. The remaining

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conditions primarily served as control for response bias, and were not considered in ERP analysis. For the “distractor-sensitive” subgroup, a mean of 50.76 hit trials ($SD = 12.19$) and 18.95 miss trials ($SD = 10.74$; Cue only: $M = 27.52$, $SD = 9.99$) remained after artifact rejection. To rule out that the unequal number of hit and miss trials influenced ERP results, an additional analysis with matched trial numbers between both conditions was conducted and confirmed the findings. The results of the analysis are provided in Supplement 2. For the “distractor-insensitive” subgroup, an average of 38.77 hit trials ($SD = 9.97$) and 32.31 cue only trials ($SD = 10.43$) were included.

As stated in our second hypothesis, the ERP study aimed to test the replicability of the early negativity and late positivity as signatures of auditory target access (Kern & Niedeggen, 2021) in a cross-modal setting. Therefore, the analysis of ERP data closely followed the procedure applied in the auditory ERP study. To assess whether the spatial and temporal clustering was appropriate for analysis of FN and P3 in the current study, grand averages for hits and misses (Figure 3A) and the global field power (GFP) based on the condition ‘cue and target, multiple distractors’ (Figure 2) were inspected. In accordance with the hypothesis, the first negative peak was well defined within the 180 – 240 ms time window and showed the expected anterior maximum. Regarding the P3, grand averages and GFP indicated that the positivity peaked later in the cross-modal than auditory presentation mode. Therefore, the 540 – 600 ms window of analysis was chosen (auditory DID: 480 – 540 ms) to determine if detected and missed targets differed in the late positive component.

In order to test the reliability of our previous ERP findings (Kern & Niedeggen, 2021), electrodes were assigned to the same two electrode clusters: an anterior electrode cluster comprised the electrodes AFz, F3, Fz, F4, FC1 and FC2 and a posterior cluster included the electrodes Cz, P3, Pz, P4, O1 and O2. Inspection of the reference-independent topographical distribution of the GFP (Figure 2) showed that the two electrode clusters adopted from the auditory DID study covered the corresponding spatial distributions of electrical activity.

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The first, confirmatory step of ERP analysis focused on the comparison between hit and miss processing regarding the two, a priori defined components of interest. First, hits and misses were contrasted regarding the FN (180 – 240 ms), which was most expressed in the anterior electrode cluster. Second, differences between both conditions in a late P3 (540 – 600 ms) with a broad spatial distribution were examined.

In addition to the assessment of replicability of FN and P3 as indicators of target access, grand averages and GFP indicated that hits and misses differed in a sustained negativity succeeding the FN. Therefore, in a second, exploratory analysis step the time windows between FN and P3 were analyzed, following the data-driven analysis procedure applied in the auditory DID study (Kern & Niedeggen, 2021). ERP activity in each experimental condition was segregated in consecutive 60 ms time windows covering the time range between FN and P3 (240 – 540 ms). Within these five temporal bins, the mean amplitude was computed for each participant, separately for each experimental condition (hit, miss) and electrode. To avoid the interpretation of possibly incidental findings in this post-hoc analysis, the sustained negativity was required to elicit significant differences between hits and misses in at least two consecutive time windows to be further discussed. A sustained global negativity was observed between 240 and 480 ms. Finally, we tested the validity of the observed ERP effects by considering the data of “distractor-insensitive” participants in additional analyses (see section 2.4).

2.4. Statistics

Data analysis was conducted using IBM SPSS Statistics 26. Behavioral data were analyzed by computing the target detection rate (correct target detection after correctly detected cue) for each experimental condition. For the behavioral study, a two-way repeated measures analysis of variance (ANOVA) containing the within-subject factors ‘SOA’ (0 ms vs. 100 ms vs. 300 ms) and ‘number of distractors’ (0 vs. 1 vs. 6-8) was conducted. For the ERP study, behavioral data of the participants considered in the comparative analysis for hits and misses

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were analyzed in a repeated measures ANOVA for the factor ‘number of distractors’ (0 vs. 1 vs. 6-8).

For ERP analysis contrasting hits and misses, data of the “distractor-sensitive” participants, who showed a sufficient number of misses (≥ 10), were considered. Mean amplitudes for hits and misses were extracted in the time range of the FN (180 – 240 ms) and P3 (540 – 600 ms). For both components of interest, a ‘condition’ (2; hit, miss) x ‘cluster’ (2; anterior, posterior) x ‘electrode’ (6 per cluster) repeated measures ANOVA was computed. To assess additional differences between both conditions, exploratory ERP analysis then focused on the comparison between hits and misses in five consecutive 60 ms time windows between FN and P3 (240 – 540 ms). For each time window, a ‘condition’ (2; hit, miss) x ‘cluster’ (2) x ‘electrode’ (6 per cluster) ANOVA was conducted. As stated in section 2.3, only sustained effects spanning at least two consecutive time windows will be further discussed. Modulatory effects of the factor ‘electrode’ will only be reported if they are significant. This did not apply for the a priori defined components FN and P3. To allow an appropriate discussion of effects, Bayes Factors (BF_{10}) were additionally calculated for the ERP components of interest (hit vs. miss) using JASP (van Doorn et al., 2021) and are provided in Supplement 3.

It was assessed whether a significant shift in topography of electrical activity occurred between the effects observed in the FN (180 – 240 ms) and sustained negativity (240 – 480 ms) time range. Therefore, activity on electrode positions was z-standardized. Based on the topographical distribution, four electrode clusters (left anterior: FC1, C3; right anterior: FC2, C4; left posterior: CP5, P3; right posterior: CP6, P4) were determined. A topographical shift was then tested running a repeated measures ANOVA including the factors ‘time’ (FN vs. SN time range), ‘laterality’ (left vs. right) and ‘caudality’ (anterior vs. posterior). To test the consistency of hit-specific effects, ERP data of the “distractor-insensitive” subgroup were included in two additional exploratory analyses. First, hit-specific effects were examined in a four-way ANOVA including the repeated-measures factors ‘condition’ (2; hit, cue only),

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‘cluster’ (2; anterior, posterior) and ‘electrode’ (6 per cluster) and the between-subject factor ‘distractor sensitivity’ (“distractor-sensitive” vs. “distractor-insensitive” subgroup). This analysis was conducted for the two a-prior defined components of interest (FN, P3), as well as for the sustained negativity identified in the exploratory analysis. Second, for these three ERP components (FN, P3, sustained negativity) the relation to target detection performance d' was examined in a correlation analyses using Pearson’s r .

In all ANOVAs, Bonferroni-corrected post-hoc comparisons were computed in case of a significant main effect or interaction. Greenhouse-Geisser corrected F-values will be reported.

3. Results

3.1 Behavioral Study

Mean target detection rates and confidence intervals in both studies are depicted in Table 1.

The repeated measures ANOVA showed that the number of preceding distractor episodes had a significant effect on target detection, $F(1.53, 29.04) = 24.78, p < .001, \eta_p^2 = .566$. Post-hoc comparisons revealed that the presentation of multiple distractors reduced target detection (0 vs. multiple distractors: $F(1, 19) = 29.83, p < .001, \eta_p^2 = .611$; 0 vs. 1 distractor: $F(1, 19) = 4.09, p = .057, \eta_p^2 = .177$; 1 vs. multiple distractors: $F(1, 19) = 28.83, p < .001, \eta_p^2 = .603$).

Furthermore, a significant effect of the factor ‘SOA’ was observed, $F(1.34, 25.49) = 5.17, p = .023, \eta_p^2 = .214$. Post-hoc tests showed that overall target detection rates were smallest in the SOA 0 ms condition (SOA 0 vs. SOA 100 ms: $F(1, 19) = 6.97, p = .016, \eta_p^2 = .268$; SOA 0 vs. SOA 300 ms: $F(1, 19) = 4.10, p = .057, \eta_p^2 = .178$; SOA 100 vs. 300 ms: $F(1, 19) = 1.79, p = .197, \eta_p^2 = .086$).

The significant interaction between the factors ‘number of distractors’ x ‘SOA’ indicated that the effect of distractors on target detection was differently expressed at the

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three SOAs, $F(2.74, 52.09) = 2.95$, $p = .046$, $\eta_p^2 = .134$. Post-hoc comparisons pointed out that multiple distractors had the strongest effect at SOA 0 ms, $F(2, 38) = 18.83$, $p < .001$, $\eta_p^2 = .498$, while an effect of multiple distractors persisted at longer cue-target SOAs (SOA 100 ms: $F(2, 38) = 17.71$, $p < .001$, $\eta_p^2 = .482$; SOA 300 ms: $F(1.44, 27.34) = 12.34$, $p = .001$, $\eta_p^2 = .394$).

False alarm rates were assessed in the ‘cue only’ control condition, where no target had been presented. Although false alarms were less frequent in the no distractor condition (8.48%, $SD = 10.84$) as compared to the multiple distractor condition (18.74 %, $SD = 21.28$), no significant difference in false alarms was observed, $F(1, 19) = 3.57$, $p = .074$, $\eta_p^2 = .158$.

3.2 ERP study

3.2.1 Behavioral data

In line with the results obtained in the behavioral study, the number of distractor episodes had a significant effect on target detection, $F(2, 40) = 8.91$, $p = .001$, $\eta_p^2 = .308$. Pairwise post-hoc comparisons showed that multiple distractors led to an impaired target detection (0 vs. multiple distractors: $F(1, 20) = 12.92$, $p = .002$, $\eta_p^2 = .392$; 0 vs. 1 distractor: $F(1, 20) = 4.06$, $p = .057$, $\eta_p^2 = .169$; 1 vs. multiple distractors: $F(1, 20) = 6.59$, $p = .018$, $\eta_p^2 = .248$).

False alarm rates were 20.61 % ($SD = 20.93$) without distractors and 26.54% ($SD = 20.51$) after multiple distractors, $F(1, 20) = 2.47$, $p = .131$, $\eta_p^2 = .110$.

To examine the reliability of the behavioral effect, the high performing, “distractor-insensitive” subgroup was included in an additional ANOVA with the between-subject factor subgroup. The main effect of number of distractors remained significant, $F(2, 64) = 4.92$, $p = .010$, $\eta_p^2 = .133$ (number of distractors x subgroup: $F(2, 64) = 5.57$, $p = .006$, $\eta_p^2 = .148$), demonstrating that the influence of multiple distractors on target detection persisted if no participants were excluded based on their task performance. The number of distractors had no influence on target detection in the “distractor-insensitive” subgroup, $F(2, 24) = .82$, $p =$

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.921, $\eta_p^2 = .007$ ($M_{0 \text{ distractor}} = 97.17$, 95% CI [94.85, 99.48]; $M_{1 \text{ distractor}} = 97.41$, 95% CI [94.73, 100.08]; $M_{6-8 \text{ distractors}} = 97.59$, 95% CI [96.17, 99.01]).

3.2.2 ERP data

Mean amplitudes of grand-averaged ERPs for hits and misses in the anterior and posterior electrode cluster for FN, P3 and sustained negativity are presented in Table 2. Grand averages for hits and misses are displayed in Figure 3A. The selection of the windows of analysis (FN: 180 – 240 ms, P3: 540 – 600ms) was based on our previous auditory DID study (Kern & Niedeggen, 2021) and the inspection of GFP (Figure 2) and grand averages. The reference-independent topographical maps confirmed that the FN was focused on frontal leads, whereas the P3 showed a broad spatial distribution with a central maximum (Figure 2). In addition, grand averages showed a sustained and widespread negativity in succession to the FN lasting for around 200 ms (Figure 3).

Figure 2

Global Field Power.

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Note. The Global Field Power (GFP) for the condition ‘cue/target, multiple distractors’ revealed a first peak of activation starting around 180 ms and reaching its maximum shortly after 200 ms. The next peak appeared around 500 ms, followed by a period of sustained activity with a maximum around 600 ms. The reference-independent maps (‘cue/target, multiple distractors’ condition) showed an anterior maximum for the FN (180 – 240 ms) and a broad, more posterior topography for the P3 (540 – 600 ms).

For ERP analysis, only trials with multiple distractors were included. The results of the statistical analysis (hit vs. miss) performed for consecutive 60 ms time windows from 180 – 600 ms and the anterior and posterior electrode cluster are presented in Table 3. For the time windows 0 – 180 ms, for which GFP and grand averages did not show relevant electrical activity, statistical analysis is provided in Supplement 1.

ERP signatures of detected vs. missed targets

Frontal Negativity (FN). As hypothesized, visual inspection of grand averages (Figure 3A) indicated a larger early negativity with anterior maximum for hits compared to missed targets. The enhanced negativity for hits between 180 and 240 ms was confirmed by a significant effect of condition, $F(1, 20) = 5.49$, $p = .030$, $\eta_p^2 = .215$ (condition x cluster: $F(1, 20) = 2.11$, $p = .162$, $\eta_p^2 = .095$).

In line with the topographical distribution expected based on the previous auditory study, hits showed significantly larger negative amplitudes than misses in the anterior electrode cluster, $F(1, 20) = 7.13$, $p = .015$, $\eta_p^2 = .263$, while no differences were observed in the posterior cluster, $F(1, 20) = 1.84$, $p = .190$, $\eta_p^2 = .084$. The topographical distribution of the FN effect (Figure 3B) revealed a shift to left-hemispheric frontal leads, contralateral to the auditory target.

P3. In contrast to the hypothesis, grand averages did not show an enhanced P3 for hits. Statistical analysis revealed that hits and misses did not differ in the expression of the late positivity between 540 and 600 ms, $F(1, 20) = 2.67$, $p = .118$, $\eta_p^2 = .118$ (condition x cluster: $F(1, 20) = 2.49$, $p = .130$, $\eta_p^2 = .111$).

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Sustained Negativity (SN). Grand averages for hits and misses (Figure 3B) indicated that the FN was succeeded by a global, long-lasting negativity with larger amplitudes for hits. As outlined in section 2.3, this observation was examined in an exploratory analysis. Significant differences between hits and misses were observed in four consecutive 60 ms time windows between 240 – 480 ms (Table 3). Consistently, the differences relied on a larger negative deflection for detected targets. Regarding the whole extended 240 – 480 ms time window, it was confirmed that hits elicited a larger sustained negativity than misses, $F(1, 20) = 12.24$, $p = .002$, $\eta_p^2 = .380$ (anterior cluster: $F(1, 20) = 9.19$, $p = .007$, $\eta_p^2 = .315$, posterior cluster: $F(1, 20) = 13.48$, $p < .001$, $\eta_p^2 = .403$). No condition x cluster interaction was observed, $F(1, 20) = .43$, $p = .519$, $\eta_p^2 = .021$. The widespread topographical distribution of the sustained negativity (Figure 3B) showed a centro-parietal maximum. However, the analysis revealed a modulation of the effect of condition by electrode position ($F(5, 100) = 4.19$, $p = .002$, $\eta_p^2 = .173$). Post-hoc comparisons showed that significant differences between hits and misses were observed at each electrode position, with exception of the right occipital electrode O2. Given the consistency of the SN effect at all other electrodes of both electrode clusters, this local deviance will not be discussed in detail.

Bayesian Statistics (BF_{10}) for the comparison between hits and misses (Supplement 3) indicated moderate evidence in favor of the alternative hypothesis for the FN ($BF_{10}=3.67$) and strong evidence for the SN ($BF_{10}=17.87$). The non-significant P3 effect provides weak evidence for the null hypothesis ($BF_{10}=0.71$).

The ERP effects in the range of the FN and SN apparently rely on the activation of different neural structures: An ANOVA including the spatial factors ‘caudality’ (anterior vs. posterior) and ‘laterality’ (left vs. right) indicated significant differences between the subsequent time ranges (time x caudality x laterality: $F(1, 20) = 5.05$, $p = .036$, $\eta_p^2 = .202$).

Figure 3

Comparison between ERPs elicited by hits and misses.

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Note. A) Grand averages for hits (red) and misses (blue) are presented separately for the anterior and posterior electrode cluster. The windows of analysis for the a priori defined ERP components of interest FN and P3 are highlighted in grey. The window for the a posteriori defined SN (240 – 480 ms) is marked in light grey. Hits were associated with a significantly larger negativity in the FN and SN range. No significant difference in a late P3 between 540 and 600 ms could be stated. B) Reference-independent topographical maps for the difference wave hits vs. misses regarding FN and SN. The earlier FN was most expressed at left (contralateral to target) fronto-central electrodes, while the subsequent SN showed a spatially more broad and not lateralized distribution over centro-parietal electrodes.

Effects of distractor sensitivity on successful target processing

In the next, exploratory analysis step, the previously identified ERP correlates of successful target detection as well as the P3 were related to distractor sensitivity. As outlined in section 2.4, the previous analysis contrasting hits and misses did not include the high performing participants with a minor number of misses, labeled as “distractor-insensitive” (n=13).

To test whether ERP components related to hits were expressed differently in both subgroups, the conditions ‘hit’ and ‘cue-only’ were contrasted for “distractor-sensitive” and “distractor-insensitive” participants. The cue only condition did not contain the short rise in amplitude defining the target and served as a baseline. Grand averages for the “distractor-

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sensitive” and “distractor-insensitive” subgroup are displayed in Figure 4. Analysis focused on the FN, sustained negativity and P3 in the previously defined temporal windows.

In the time window of the FN (180 – 240 ms), both subgroups showed a larger negative deflection on anterior electrodes for hits compared to ‘cue only’ control condition. Statistical analysis confirmed the main effect of condition, $F(1, 32) = .05$, $p = .001$, $\eta_p^2 = .306$. Importantly, the expression of the frontal negativity was not affected by distractor sensitivity (condition x subgroup: $F(1, 32) = .05$, $p = .815$, $\eta_p^2 = .002$).

For the sustained negativity (240 – 480 ms), a larger amplitude for hits was expressed in both subgroups, as indicated by the main effect of condition, $F(1, 32) = 9.75$, $p = .004$, $\eta_p^2 = .233$. Likewise the FN, the expression of this component was not modulated by subgroup affiliation (condition x subgroup: $F(1, 32) = .46$, $p = .500$, $\eta_p^2 = .014$).

For the late positivity (540 – 600 ms), a different pattern emerged. In contrast to the “distractor-sensitive” participants, for which grand averages indicated no difference between conditions, hits showed an enhanced positivity compared to cue only in the “distractor-insensitive” subgroup (Figure 4). The ANOVA failed to detect a significant main effect of condition, $F(1, 32) = 3.74$, $p = .062$, $\eta_p^2 = .105$, while hits descriptively showed larger positive amplitudes than cue only (condition x subgroup: $F(1, 32) = .05$, $p = .066$, $\eta_p^2 = .102$). In the posterior electrode cluster, post-hoc analysis following a significant main effect of subgroup, $F(1, 32) = 5.71$, $p = .023$, $\eta_p^2 = .151$, revealed a significantly larger P3 for hits for “distractor-insensitive” participants, $F(1, 12) = 7.48$, $p = .018$, $\eta_p^2 = .384$, but no difference between conditions in the “distractor-sensitive” subgroup, $F(1, 20) = .08$, $p = .775$, $\eta_p^2 = .004$. Group affiliation had no impact in the anterior cluster, $F(1, 32) = .00$, $p = .941$, $\eta_p^2 = .000$.

Figure 4

Grand averages for the “distractor-sensitive” and “distractor-insensitive” subgroup.

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Note. Grand averages for hits (red) and cue only control condition (black) presented separately for participants with ≥ 10 misses in the multiple distractor condition (“distractor-sensitive” subgroup; left panel) and participants with less than 10 misses (“distractor-insensitive” subgroup; right panel) and both electrode clusters. Black frames highlight the three windows of analysis (180 – 240 ms FN, 240 – 480 ms sustained negativity, 540 – 600 ms P3).

Relationship between ERP expression and target discrimination

While the hit-specific frontal negativity and sustained negativity appeared to be expressed independent of individual distractor sensitivity, subgroup analysis indicated a possible link between P3 and task performance. Therefore, in another exploratory analysis, we examined correlations between FN, sustained negativity, P3 and target discrimination. Data of the thirteen high-performing participants were again included to validate ERP results. This led to a sample of 34 participants for the correlation analysis (20 women; 19 — 34 years of age; M_{age} : 24.33, SD: 4.99). For each participant, we determined d' ($z_{\text{hit}} - z_{\text{false alarm}}$) as discrimination index depicting the reliability of response behavior towards targets. Results of the correlation analysis are presented in Figure 5.

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First, d' values were correlated with the FN (180 – 240 ms, anterior electrode cluster). To quantify the expression of the FN effect, the difference between mean amplitudes for hits and cue only ($FN_{hit} - FN_{cue}$) was computed for each participant. Target detection performance was not correlated to FN, $r(32) = .005$, $p = .979$, indicating that this hit-specific effect cannot be explained by differences in detection performance (Figure 5A).

Second, for the sustained negativity (SN), mean amplitudes in the 240 – 480 ms time window were computed including both electrode clusters due to the widespread topography of this component. The SN effect ($SN_{hit} - SN_{cue}$) showed no link to participant's target discrimination, $r(32) = -.039$, $p = .825$ (Figure 5B).

Third, the correlation between P3 amplitude (480 – 660 ms, posterior cluster) and participant's response behavior was examined. Substantiating the results of the subgroup analysis, a reliable response to targets was strongly correlated to a larger P3 effect ($P3_{hit} - P3_{cue}$), $r(32) = .519$, $p = .002$ (Figure 5C).

Figure 5

Scatterplots of the correlations (Pearson's r) between the ERP components Frontal negativity (FN), Sustained Negativity (SN) and P3, respectively, and target discrimination.

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Note. The discrimination index d' ($Z_{\text{hit}} - Z_{\text{false alarm}}$) provides an indicator of the reliability of the participant's response behavior. A) Correlation between FN effect ($\text{FN}_{\text{hit}} - \text{FN}_{\text{cue}}$) and d' , calculated for the 180 – 240 ms time window and the anterior electrode cluster. FN and d' were not correlated. B) Correlation between SN effect ($\text{SN}_{\text{hit}} - \text{SN}_{\text{cue}}$) and d' for the 240 – 480 ms window and both electrode clusters. No correlation was observed. C) Correlation between P3 effect ($\text{P3}_{\text{hit}} - \text{P3}_{\text{cue}}$) and d' within the 480 – 660 ms time window and the posterior electrode cluster. P3 and detection performance d' showed a significant, positive correlation.

4. Discussion

4.1 Summary of results

In two cross-modal experiments, an auditory target, which was preceded or accompanied by a visual cue, had to be detected. Auditory distractors sharing the target's features could appear in the pre-cue epoch and should be ignored. Unimodal findings were expanded by confirming that a target detection deficit (distractor-induced deafness, DID) can also be observed if the cue is presented in a different sensory modality than the target. This effect

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critically depended on the presence of multiple distractor epochs, whereas a single distractor was not sufficient to reduce hit rates.

In line with the hypothesis, correct target report was associated with a larger frontal negativity (FN) between 180 and 240 ms, suggesting that this early frontal component is a reliable signature of auditory awareness. In contrast to our hypothesis, no significant difference between hits and misses regarding a larger late positive component (P3) was observed.

Exploratory analysis indicated that target detection in a cross-modal setting was additionally characterized by a sustained negativity succeeding the FN. Both ERP markers of successful target detection – FN and sustained negativity – were expressed similarly in participants with impaired target detection after multiple distractors (“distractor-sensitive”), and in participants showing no impairment of target detection (“distractor-insensitive”).

4.2 Multiple distractors impair target detection in a cross-modal setting

Our behavioral data were in favor of the first hypothesis and showed that the inhibitory effect induced by the presence of multiple distractors does not depend on the sensory modality of the cue. It also supports the notion that attentional resources spend in the processing of the visual and auditory stream are shared across modalities.

What are implications of the observed transferability of distractor-induced deafness from uni- to cross-modal setting? The current results are in line with the functional process previously proposed for unimodal distractor effects (Niedeggen et al., 2012; Zhang et al., 2009). The cross-modal DID exhibits similar behavioral characteristics as the visual and auditory effect (Hesselmann et al., 2006; Kern & Niedeggen, 2021) and the same theoretical assumptions can be applied: distractors, which share the target’s features, activate a negative attentional set, and the cue functions as a release signal of this inhibition (Niedeggen et al., 2015; Zhang et al., 2009). However, inhibition of target/distractor features is not released immediately and can thus impair subsequent target detection. Importantly,

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inhibition of target features is not sufficiently triggered by a single distractor and a cumulative nature of the effect can be assumed (Hesselmann et al., 2006). The inhibitory model implies that a target detection deficit should occur if distractors and target share stimulus features, irrespective of the modality in which a cue is presented.

The findings suggest that monitoring a visual stream for a cue does not change the processing and impact of auditory distractors when compared to a purely auditory set up. Target-like distractors can disrupt target detection within the auditory modality, regardless of the cue being presented in the same or a different sensory modality. Previous audiovisual research (Kamke & Harris, 2014; Turatto et al., 2002) indicated that distractor events in one modality can alter processing and detection of a relevant stimulus in another modality. The current study shows that a cue appearing in a different modality than distractors and target can function as release signal of the distractor-induced inhibition of target features and that the modality of the cue apparently plays no or only a subordinate role for the DID effect.

The observation of a cross-modal DID effect stands in contrast to some studies on the cross-modal attentional blink, which found the AB to be either completely absent (Duncan et al., 1997; Van der Burg et al., 2007) or reduced compared to unimodal stimulus presentation (Arnell & Larson, 2002). This indicates that different mechanisms are underlying the two related phenomena. The AB has often been explained in terms of an occupation of capacity-limited central resources by the first target, preventing T2 from being processed in working memory if it is presented in quick temporal succession to T1 (for a review of theories: (Dux & Marois, 2009)). Arnell and Jenkins (2004) put forward a model to explain the inconsistent findings regarding a cross-modal AB. They suggested that the more consistent and larger unimodal effects are caused by a combination of central and within-modality processing limitations, while only central limitations apply to the cross-modal AB, since T1 and T2 are presented in different modalities. In contrast, for DIB/DID the allocation of attentional resources within the target's (and distractor's) modality is most likely the crucial

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factor. Future research is necessary to examine the consistency of a distractor-induced target detection deficit in different cross-modal settings.

4.3 ERP signatures of access to an auditory target in a cross-modal task

4.3.1 Frontal Negativity: A reliable ERP correlate of auditory awareness

In line with previous results (Kern & Niedeggen, 2021), we confirmed a reliable ERP signature of an upcoming correct target detection in the time range 180 to 240 ms. Hits were associated with an increase in amplitude of a frontal negativity compared to missed targets. Bayesian statistics showed moderate evidence for the hypothesis, which is furthermore strengthened by the fact that the finding of a hit-specific FN provides a successful replication.

This early ERP component has previously been associated with the (re-)activation of attentional control processes in terms of a Processing Negativity (Näätänen et al., 2011) after inhibition of target features is released. The assumed functional process is congruent with the idea that the detection of a target in the DID task critically depends on the release of the negative attentional set previously defined by the distractors.

Strikingly, other recent studies using different auditory tasks have also found a fronto-central negativity around 200 ms, which was focused on contralateral electrodes and accompanied subjective awareness of a target measured in terms of target report (Eklund et al., 2019, 2021; Eklund & Wiens, 2019; Schlossmacher et al., 2021). The term ‘auditory awareness negativity’ (AAN) has been suggested for this component, in analogy to the visual awareness negativity (VAN) for perceived visual stimuli, which typically occurs around 200 ms on posterior nodes (for a review on VAN (Förster et al., 2020; Koivisto & Revonsuo, 2010). The observed similarities indicate that the frontal process observed in the current study is related to the AAN. Previous research has characterized the AAN as a marker of auditory consciousness with its neural sources likely to be located in auditory cortical areas (Dembski et al., 2021; Wiegand & Gutschalk, 2012).

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Dembski et al. (2021) recently suggested an early ‘perceptual awareness negativity’ as putative neural correlate of consciousness (NCC) occurring in different sensory modalities. Notably, contradicting this supramodal model, for distractor-induced blindness no modulation of early visual evoked potentials by target awareness was found for the features motion (Niedeggen et al., 2002) and orientation (Niedeggen et al., 2015). This indicates that NCCs for this distractor-induced effect might differ between sensory modalities.

While the frontal negativity appears to be a correlate of auditory target detection, we found no indicators that the expression of this component is related to individual differences in detection performance. FN amplitude was not modulated in the subgroup of “distractor-insensitive” participants and it showed no correlation to target discrimination. These findings suggest that the process underlying the FN does not reflect general sensitivity to distractors of an observer. Instead, our results indicate that the FN depicts momentary access to an auditory target event.

4.3.2 Sustained negativity: a process specific to target detection in the cross-modal setting?

The FN was succeeded by a hit-specific sustained negativity between 240 and 480 ms, which has not been observed in our previous auditory study. In contrast to the FN, the sustained negativity was not limited to frontal electrodes, but showed a more global distribution. Like the FN, the sustained negativity cannot be related to the participant’s overall detection performance, but appears to indicate processing of later detected targets. As revealed by the statistical comparison of topographies, the SN can be segregated from the FN.

This finding provides first evidence of a specific cross-modal effect in distractor-induced deafness. Bayesian statistics indicated strong evidence for a difference between hits and misses in this long-lasting component. If target detection requires the integration of a relevant auditory and visual signal, the FN is succeeded by a temporal and topographical expansion of activity. Inspection of ERP waves associated with cue only (Fig. 4 left)

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suggested that the processing of the visual cue might contribute to the sustained negativity. In line with this assumption, a centro-parietal negativity in the SN time range was elicited by cue only (see Supplement 4).

While this ERP effect certainly requires replication, we tentatively suggest that the sustained negativity can be related to a corresponding finding observed in previous cross-modal research: an enhanced fronto-central negativity starting around 200 ms and lasting for several hundred milliseconds was elicited by an auditory stimulus and a simultaneously occurring, attended visual stimulus (Busse et al., 2005). The authors attributed the effect to an enhancement in neural processing of the auditory stimulus triggered by attending a concurrent visual stimulus. In the same way, Talsma et al. (2010) suggested that such a long-lasting, “late” processing negativity mirrors a cross-modal spread of attention during multisensory integration. Future studies will have to confirm the idea that the sustained negativity might reflect a cross-modal attentional spread. This process will have to be segregated from a contingent negative variation (CNV), which has been related to the optimization of cognitive resource allocation (Arjona et al., 2014; Falkenstein et al., 2003; Kononowicz & Penney, 2016).

4.3.3 P3 does not indicate conscious target processing in the cross-modal DID task

In previous unimodal studies, a modulation of the late posterior P3 by target awareness was observed for both DIB and DID (Kern & Niedeggen, 2021; Niedeggen et al., 2015), as well as for the attentional blink (Dell'Acqua et al., 2015; Sergent et al., 2005). More specifically, the processing of missed targets has been associated with a diminished and sometimes absent P3 when compared to perceived targets. These and other findings led to the conclusion that the P3 might be an electrophysiological marker of updating processes into working memory and a valid correlate of conscious access (Dehaene et al., 2011; Naccache et al., 2016; Sergent et al., 2005; Ye et al., 2019). Considering the previous results, we expected to find a P3 effect for hits in the cross-modal setting of the current study.

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However, in contrast to the hypothesis, target detection was not associated with a significantly larger P3 amplitude. It is important to consider, however, that the non-significant P3 effect provides only weak evidence for the absence of an effect according to Bayesian statistics. The notion of the P3 as ERP correlate of consciousness has already been challenged repeatedly (Dembski et al., 2021; Koch et al., 2016; Schlossmacher et al., 2021; Schlossmacher et al., 2020; Schröder et al., 2020; Verleger, 2020), and alternative functional processes underlying the P3 were proposed. One suggestion that was put forward is the association of the P3 with post-perceptual processes reflecting decision-making and target report (Cohen et al., 2020; Koivisto et al., 2016; Mazzi et al., 2020; Pitts et al., 2014). In line with this notion, P3 amplitude has been found to be enhanced if participants are more certain of their decision regarding a target (Hillyard et al., 1971; Johnson, 1984; Luck, 2005; Squires et al., 1973).

A corresponding link between P3 and decision certainty is indicated by our correlation analysis, which revealed a strong positive correlation between P3 effect and target detection performance d' . This suggests that for participants with an overall better task performance (more hits in relation to false alarms) hit trials were accompanied by a larger P3 in comparison to participants with poorer target discrimination. In the same way, the subgroup analysis showed that hits elicited a larger posterior P3 than cue only – but solely in the high performing subgroup producing few misses. We therefore tentatively suggest that the P3 primarily mirrors decision certainty and target discrimination ability in the current study. The connection between distractor sensitivity and certainty – as possibly reflected in the P3 amplitude – is an interesting avenue for future research.

4.4 Limitations and future research

One concern regarding the current study is related to the number of participants who had to be excluded from ERP analysis comparing hits and misses due to a small number of misses. In thirteen participants, the number of miss trials was not sufficient to compute a reliable ERP average (<10 misses). The rate of exclusion due to an insufficient number of miss trials was

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higher than in the previous unimodal ERP study (auditory study: 6 out of 45 participants (13.3 %); current study: 13 out of 38 participants (34.2 %)). This observation limits our conclusion on the cross-modal nature of the DIB/DID effect (see 4.2). However, it is important to note that we observed a reliable distractor effect in the behavioral study, where no participants were excluded due to ceiling effects, and that the distractor effect persisted in the ERP study, if “distractor-insensitive” participants were included in the analysis. Furthermore, by including the subgroup of “distractor-insensitive” participants in additional analyses, it was shown that the hit-specific ERP effects were also observed in high performing participants and the correlation analysis provided insight into possible links between task performance and ERPs. Future studies need to determine if the higher number of participants performing at ceiling indicates that more participants are “immune” to distractors in a cross-modal setting. Furthermore, inter-individual differences in DID task performance and their potential causes, such as executive working memory functioning or attentional focus (Willems & Martens, 2016), should be examined.

Due to the overall much smaller number of misses than hits, a second limitation of our study is that the analysis of the relation between P3 and the discrimination ability is restricted to hits. A corresponding analysis for misses is not possible because of the exclusion of high-performing participants with a lack of misses. This analysis – foreseen in future research – might allow us to decide whether the P3 amplitude is primarily related to the post-perceptual decision process, or to a depletion of attentional resources in a common attentional system. Furthermore, the unequal number of hits and misses is a limitation of this cross-modal paradigm that might influence ERP analysis. To address this concern, an analysis with matched trial numbers was conducted, which confirmed the findings for FN, SN and P3.

A third critical point is that while analysis regarding FN and P3 was based on a priori hypothesis, the examination of additional effects and the subgroup analysis were exploratory and data-driven instead of theory-driven. Therefore, results regarding the sustained

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negativity and the analysis including “distractor-insensitive” participants should be considered as preliminary and need to be followed up in future studies.

Another aspect that needs to be carefully considered is the possibility that the irrelevant second auditory stream caused informational masking effects influencing target detection (Gutschalk et al., 2008). Importantly, we can rule out that the influence of distractors on target detection can be explained by masking, since stream 2 was consistently present in all distractor conditions. The target was defined by a feature (i.e. rise in amplitude) not occurring in the irrelevant stream and frequency ranges in both streams did not overlap, which make a substantial impact of masking effects rather unlikely. However, based on the behavioral data we cannot rule out that informational auditory masking has occurred in addition to the distractor-evoked effect and that it might have led to an overall reduction of target detection rates in all experimental conditions.

4.5 Conclusion

In summary, the current study shows that distractor-induced deafness can be transferred from unimodal to a cross-modal setting. Multiple auditory distractors impaired the detection of a target in the same sensory modality, independent of a cue appearing in the visual modality.

Interpreting our results following the taxonomy of Aru et al. (2012), which suggests a distinction between processes preceding and following conscious experience and true NCC, the findings suggest that the early frontal negativity is a NCC of auditory awareness – or at least a necessary prerequisite. In contrast, the P3 might reflect a post-perceptual process possibly linked to decision certainty in this cross-modal task. The role of a sustained negativity for target perception in cross-modal processing needs to be explored.

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Tables

Table 1

Target detection rates

Distractors	Behavioral study			ERP study
	SOA 0 ms	SOA 100 ms	SOA 300 ms	SOA 0 ms
0	$M = 88.17$	$M = 90.59$	$M = 89.92$	$M = 83.79$
	CI [81.58, 94.75]	CI [83.52, 97.65]	CI [83.11, 96.72]	CI [76.19, 91.39]
1	$M = 79.93$	$M = 90.39$	$M = 84.42$	$M = 78.65$
	CI [69.67, 90.18]	CI [84.53, 96.26]	CI [74.74, 94.11]	CI [71.75, 85.54]
6-8	$M = 60.58$	$M = 72.62$	$M = 73.34$	$M = 70.52$
	CI [48.85, 72.31]	CI [61.74, 83.50]	CI [62.75, 85.93]	CI [64.18, 76.86]

Note. Mean (in %) and 95% confidence intervals (CIs) of the mean for averaged correct target detection, reported separately for each distractor- and SOA condition and for behavioral and ERP study.

For the ERP study, behavioral data of the participants considered in the comparative ERP analysis between hits and misses (“distractor-sensitive” subgroup) are depicted.

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Table 2

Mean ERP amplitudes (in μV) and 95% confidence intervals (CIs) for hits and misses.

Condition	Electrode cluster	ERP component		
		180 - 240 ms (FN)	240 - 480 ms (SN)	540 - 600 ms (P3)
Hit	frontal	$M = -1.987$	$M = -1.836$	$M = 5.148$
		95% CI	95% CI	95% CI
		[-2.54, -1.44]	[-2.45, -1.23]	[3.46, 6.84]
	parietal	$M = -1.163$	$M = -2.105$	$M = 3.29$
		95% CI	95% CI	95% CI
		[-1.52, -.80]	[-2.61, -1.60]	[2.16, 4.42]
Miss	frontal	$M = -1.135$	$M = -.824$	$M = 5.966$
		95% CI	95% CI	95% CI
		[-1.77, -.50]	[-1.62, -.034]	[4.08, 7.85]
	parietal	$M = -.757$	$M = -1.234$	$M = 3.544$
		95% CI	95% CI	95% CI
		[-1.31, -.19]	[-1.76, -.71]	[2.16, 4.93]

Note. Descriptive values are presented for the FN, the sustained negativity (SN) between 240 and 480 ms and the P3, separately for the anterior and posterior electrode cluster.

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Table 3

Summary of the statistical analysis for the ERP data between 180 and 600 ms after cue/target onset.

		180 - 240 (FN)	240 - 300	300 - 360	360 - 420	420 - 480	480 - 540	540 - 600 (P3)
Hit vs. Miss	Condition	$F(1, 20) = 5.49$	$F(1, 20) = 8.91$	$F(1, 20) = 7.71$	$F(1, 20) = 7.35$	$F(1, 20) = 6.99$	$F(1, 20) = 2.09$	$F(1, 20) = 2.67$
		$p = .030$	$p = .007$	$p = .012$	$p = .013$	$p = .016$	$p = .163$	$p = .118$
		$\eta = .215$	$\eta = .308$	$\eta = .278$	$\eta = .296$	$\eta = .259$	$\eta = .095$	$\eta = .118$
	Condition x Cluster	$F(1, 20) = 2.11$	$F(1, 20) = .75$	$F(1, 20) = .52$	$F(1, 20) = 1.31$	$F(1, 20) = .24$	$F(1, 20) = 2.09$	$F(1, 20) = 2.49$
		$p = .162$	$p = .398$	$p = .480$	$p = .267$	$p = .628$	$p = .163$	$p = .130$
		$\eta = .095$	$\eta = .036$	$\eta = .025$	$\eta = .061$	$\eta = .012$	$\eta = .095$	$\eta = .111$
	Post-Hoc anterior Cluster	$F(1, 20) = 7.13$	$F(1, 20) = 1.77$	$F(1, 20) = .96$	$F(1, 20) = 1.43$	$F(1, 20) = 2.14$		
		$p = .015$	$p = .198$	$p = .338$	$p = .245$	$p = .159$		
		$\eta = .263$	$\eta = .081$	$\eta = .046$	$\eta = .067$	$\eta = .097$		
	Post-Hoc posterior Cluster	$F(1, 20) = 1.84$	$F(1, 20) = 2.94$	$F(1, 20) = 2.92$	$F(1, 20) = 1.29$	$F(1, 20) = 1.85$		
		$p = .190$	$p = .102$	$p = .103$	$p = .269$	$p = .188$		
		$\eta = .084$	$\eta = .128$	$\eta = .127$	$\eta = .061$	$\eta = .085$		

Note. The two conditions hits and misses were compared within consecutive 60 ms time windows including the factor electrode cluster (anterior, posterior). In case of a significant main effect of condition or a condition x cluster interaction (highlighted in bold), post-hoc tests were conducted. The analysis for the first three time windows (0 – 180 ms), for which GFP and grand averages indicated no effects, is provided in supplement 1.

Figure Captions

Figure 1. *Experimental design of both cross-modal experiments.*

Note. Participants heard a continuous tone on the right ear (270 - 330 Hz), which could contain the target stimulus. On the left ear, a sequence of pure tones (1,800 - 2,200 Hz) was presented simultaneously. This second stream was not task relevant and is therefore not depicted above. Simultaneous to the auditory streams, a RSVP containing a 'preloader' symbol was presented on the screen in front of the participant. The preloader symbol changed at a rate of 100 ms per frame, creating the impression of a clockwise motion. A small white circle (cue) could appear as a singular event, positioned randomly at the place of one of the 8 bars. A short increase (100 ms duration) in amplitude in the continuous tone was defined as target, but only if it was accompanied by the white circle. In the behavioral study, the cue could also precede the target. Increases in amplitude occurring before the cue were defined as distractors and should be ignored.

Figure 2. *Global Field Power.*

Note. The Global Field Power (GFP) for the condition 'cue/target, multiple distractors' revealed a first peak of activation starting around 180 ms and reaching its maximum shortly after 200 ms. The next peak appeared around 500 ms, followed by a period of sustained activity with a maximum around 600 ms. The reference-independent maps ('cue/target, multiple distractors' condition) showed an anterior maximum for the FN (180 – 240 ms) and a broad, more posterior topography for the P3 (540 – 600 ms).

Figure 3. *Comparison between ERPs elicited by hits and misses.*

Note. A) Grand averages for hits (red) and misses (blue) are presented separately for the anterior and posterior electrode cluster. The windows of analysis for the a priori defined ERP components of interest FN and P3 are highlighted in grey. The window for the a posteriori

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defined SN (240 – 480 ms) is marked in light grey. Hits were associated with a significantly larger negativity in the FN and SN range. No significant difference in a late P3 between 540 and 600 ms could be stated. B) Reference-independent topographical maps for the difference wave hits vs. misses regarding FN and SN. The earlier FN was most expressed at left (contralateral to target) fronto-central electrodes, while the subsequent SN showed a spatially more broad and not lateralized distribution over centro-parietal electrodes.

Figure 4. *Grand averages for the “distractor-sensitive” and “distractor-insensitive” subgroup.*

Note. Grand averages for hits (red) and cue only control condition (black) presented separately for participants with ≥ 10 misses in the multiple distractor condition (“distractor-sensitive” subgroup; left panel) and participants with less than 10 misses (“distractor-insensitive” subgroup; right panel) and both electrode clusters. Black frames highlight the three windows of analysis (180 – 240 ms FN, 240 – 480 ms sustained negativity, 540 – 600 ms P3).

Figure 5. *Scatterplots of the correlations (Pearson’s r) between the ERP components Frontal negativity (FN), sustained negativity (SN) and P3, respectively, and target discrimination.*

Note. The discrimination index d' ($Z_{\text{hit}} - Z_{\text{false alarm}}$) provides an indicator of the reliability of the participant’s response behavior. A) Correlation between FN effect ($\text{FN}_{\text{hit}} - \text{FN}_{\text{cue}}$) and d' , calculated for the 180 – 240 ms time window and the anterior electrode cluster. FN and d' were not correlated. B) Correlation between SN effect ($\text{SN}_{\text{hit}} - \text{SN}_{\text{cue}}$) and d' for the 240 – 480 ms window and both electrode clusters. No correlation was observed. C) Correlation between P3 effect ($\text{P3}_{\text{hit}} - \text{P3}_{\text{cue}}$) and d' within the 480 – 660 ms time window and the posterior electrode cluster. P3 and detection performance d' showed a significant, positive correlation.

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Figures

Figure 1

Figure 2

Figure 3

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Figure 4

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Figure 5