

Fachbereich Erziehungswissenschaften und Psychologie  
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# Electrophysiological correlates of auditory awareness during distractor-induced deafness

## **Dissertation**

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## Abstract

Task-relevant and distracting stimuli in all sensory modalities are in constant competition for selective attention and access to consciousness. If distractors and targets share features, target awareness can be impaired due to distractor-driven inhibitory processes. This transient “blindness” for the target has been demonstrated with the distractor-induced blindness (DIB) paradigm (Sahraie et al., 2001). In the DIB paradigm, a cue indicates the target and target-like distractors can occur preceding the cue. This experimental set-up allows a direct contrast between detected and missed targets under identical sensory stimulation, making it suitable for the investigation of neural correlates of consciousness. Consciousness research has tried to disentangle reliable neural markers of conscious perception since the 1990ies. While some progress has been made, no final answers have been found. The majority of research in the field of consciousness has been conducted in the visual modality. Likewise, the DIB task has never been applied outside of vision.

This dissertation revolves around two main research questions. First, this thesis aims to adapt the DIB paradigm to auditory and cross-modal settings for the first time. The goal is to investigate whether the distractor effect on target detection is a phenomenon observable across sensory modalities. Second, this thesis aims to examine electrophysiological correlates of auditory awareness in auditory and cross-modal conditions using event-related brain potentials (ERPs). These research aims were investigated in three consecutive studies.

In Study I, *distractor-induced deafness* (DID) was established by revealing that multiple distractors also hinder target detection in the auditory modality. Furthermore, an early frontal and a late centro-parietal (P3) neural signature of auditory awareness was observed. Study II examined to what extent the findings of Study I can be replicated in a cross-modal DID task, including an auditory target and a visual cue. Distractor-induced deafness persisted in this cross-modal setting and the early correlate of auditory awareness was successfully confirmed. A potential cross-modal marker of auditory target access

succeeded the frontal negativity. In contrast to unimodal findings, the late P3 was correlated with the individual task performance, and did not indicate target awareness. In Study III, a cross-modal DIB effect was investigated. While this effect could consistently be stated throughout three behavioral experiments, the distractor effect showed a smaller magnitude than the visual DIB and the cross-modal effect for reversed modalities. Neither the auditory cue feature nor the visual target feature could account for this finding. This indicates that an auditory cue might be especially efficient in redirecting attention to a visual target.

In summary, this dissertation shows that multiple preceding distractors, which share the target's features, cannot only make an observer "blind", but also "deaf" for a task-relevant stimulus. This inhibitory effect of distractors on target detection is not restricted to unimodal settings but extends to cross-modal stimulus conditions. In expansion of previous visual research, the findings therefore revealed a generality of the distractor-induced effect across sensory modalities. However, some modality-specific differences were observed and need to be considered. Furthermore, ERP results emphasized an early frontal negativity as reliable marker of auditory awareness. In contrast, the late P3 component and its underlying processes were not consistently linked to auditory target access. The electrophysiological findings provide a contribution to the ongoing search for signatures of consciousness and support a significant role of early processing for auditory consciousness.

## Zusammenfassung

Aufgabenrelevante und ablenkende Reize aus allen Sinnesmodalitäten befinden sich in ständigem Wettstreit um selektive Aufmerksamkeit und den Zugang zum Bewusstsein. Falls Distraktoren und Zielreize Merkmale teilen, kann die bewusste Wahrnehmung des Zielreizes aufgrund von durch die Distraktoren ausgelösten inhibitorischen Prozessen beeinträchtigt sein. Diese vorübergehende „Blindheit“ für den Zielreiz wurde mit dem Paradigma der distraktor-induzierten Blindheit (DIB) (Sahraie et al., 2001) demonstriert. In dem DIB Paradigma wird ein Zielreiz durch einen Hinweisreiz angezeigt und zielreizgleiche Distraktoren können vor dem Hinweisreiz auftreten. Dieser Versuchsaufbau ermöglicht die direkte Kontrastierung von erkannten und verpassten Zielreizen unter identischer sensorischer Stimulation, wodurch er geeignet ist, neuronale Korrelate des Bewusstseins zu untersuchen. Die Bewusstseinsforschung versucht seit den 1990er Jahren neuronale Marker der bewussten Wahrnehmung zu identifizieren. Obwohl schon einige Fortschritte erzielt werden konnten, fehlt es bislang noch an abschließenden Antworten. Die Mehrheit der Bewusstseinsstudien wurde in der visuellen Sinnesmodalität durchgeführt. Ebenso wurde auch die DIB Aufgabe bislang niemals außerhalb der visuellen Wahrnehmung eingesetzt.

Diese Dissertation widmet sich zwei zentralen Forschungsfragen. Erstens soll das DIB Paradigma erstmals an auditive und cross-modale Reizbedingungen angepasst werden. Es soll somit untersucht werden, ob der Effekt von Distraktoren auf die Zielreizerkennung ein modalitätsübergreifend zu beobachtendes Phänomen ist. Zweitens zielt diese Arbeit darauf ab, elektrophysiologische Korrelate des auditiven Bewusstseins in auditiven und cross-modal Bedingungen mittels ereigniskorrelierter Potentiale (EKPs) zu identifizieren. Diese Forschungsziele wurden in drei aufeinander aufbauenden Studien untersucht.

In Studie I konnte eine distraktor-induzierte Taubheit (DID) etabliert werden, indem gezeigt wurde, dass multiple Distraktoren die Zielreizerkennung auch in der auditiven Modalität behindern. Darüber hinaus konnte eine frühe frontale und eine späte zentro-parietale (P3) neuronale Signatur des auditiven Bewusstseins festgestellt werden. Studie II

untersuchte, inwiefern die Ergebnisse von Studie I in einer cross-modalen DID Aufgabe, welche einen auditiven Zielreiz und einen visuellen Hinweisreiz beinhaltet, repliziert werden können. Die distraktor-induzierte Taubheit persistierte in diesen cross-modal Gegebenheiten und das frühe Korrelate der bewussten auditiven Wahrnehmung konnte erfolgreich bestätigt werden. Diese frontale Negativität wurde gefolgt von einem potentiellen cross-modalen Marker des auditiven Zielreizzugriffs. Im Gegensatz zu unimodalen Befunden war die späte P3 mit der individuellen Performanz in der Aufgabe korreliert, und bildete nicht die bewusste Wahrnehmung des Zielreizes ab. In Studie III wurde der cross-modale DIB-Effekt untersucht. Dieser Effekt konnte konsistent in allen drei Verhaltensexperimenten beobachtet werden, jedoch war die Größe des Distraktoreffektes kleiner als die visuelle DIB und der cross-modale Effekt für umgekehrte Sinnesmodalitäten. Weder das Merkmal, das den auditiven Hinweisreiz definierte, noch das Merkmal, welches den visuellen Zielreiz definierte, konnten diesen Befund erklären. Dies deutet darauf hin, dass ein auditiver Hinweisreiz besonders effektiv darin ist, die Aufmerksamkeitsausrichtung auf den visuellen Zielreiz zu fördern.

Zusammenfassend zeigt diese Dissertation, dass die wiederholte Darbietung von Distraktoren, welche Zielreizmerkmale teilen, nicht nur „blind“, sondern auch „taub“ für aufgabenrelevante Reize machen kann. Dieser hemmende Effekt von Distraktoren auf die Zielreizerkennung ist nicht auf unimodale Reizumgebungen beschränkt, sondern lässt sich auch auf cross-modale Bedingungen übertragen. In Erweiterung früherer visueller Studien zeigen die Befunde folglich eine Allgemeingültigkeit des Effektes über sensorische Modalitäten hinweg. Jedoch wurden modalitätsspezifische Unterschiede beobachtet, welche berücksichtigt werden müssen. Darüber hinaus verdeutlichten die EKP Befunde die Bedeutung einer frühen frontalen Negativität als zuverlässigen Marker auditiven Bewusstseins. Die späte P3 Komponente und ihre zugrundeliegenden Prozesse zeigte dagegen keinen konsistenten Zusammenhang mit dem auditiven Zielreizzugriff. Die elektrophysiologischen Erkenntnisse liefern einen Beitrag zur anhaltenden Suche nach Signaturen des Bewusstseins und unterstützen eine tragende Rolle früher Verarbeitungsprozesse für das auditive Bewusstsein.

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## List of abbreviations

AAN	Auditory awareness negativity
AB	Attentional blink
ANOVA	Analysis of variance
CAC	Contingent attentional capture
CB	Change blindness
CI	Confidence interval
DIB	Distractor-induced blindness
DID	Distractor-induced deafness
EEG	Electroencephalogram
EOG	Electrooculogram
ERP	Event-related potential
fMRI	Functional magnetic resonance imaging
FN	Frontal negativity
GNWT	Global neuronal workspace theory
IB	Inattention blindness
IIT	Integrated Information Theory
ISI	Inter stimulus interval
NCC	Neural correlate of consciousness
RPT	Recurrent processing theory
RSAP	Rapid serial auditory presentation
RSVP	Rapid serial visual presentation
SD	Standard deviation
SN	Sustained negativity
SOA	Stimulus onset asynchrony
VAN	Visual awareness negativity

## **Overview of the contents of this cumulative dissertation**

### Chapter 1: Introduction

Following a general introduction into the field of consciousness research, the paradigm of distractor-induced blindness (DIB), which was applied in an adapted version in all studies comprised in this dissertation, is outlined. Consecutively, the assumed model behind DIB and underlying theories of attentional selection and inhibition are described. A selection of related paradigms, which are often applied in consciousness research, is introduced, and findings regarding electrophysiological correlates of awareness in the visual modality are shortly reviewed. Finally, the question of the transferability of behavioral and electrophysiological results from visual to auditory and cross-modal stimulus conditions is addressed. The section closes with a brief outline of the research agenda of this dissertation.

### Chapter 2: Summary of the aims and research questions of this dissertation

This chapter introduces the research questions and hypotheses of the studies included in this thesis. In addition, the methodological approach, samples, experimental manipulations and dependent variables are described.

### Chapters 3 – 5: Original studies

The three chapters include the published or submitted manuscripts constituting the core of this dissertation.

### Chapter 6: General discussion

In the final chapter, the findings are first summarized and then discussed with regard to their implications for the DIB model. Findings acquired with the DIB paradigm are compared between sensory modalities. Based on the experimental results, the current state regarding electrophysiological correlates of auditory awareness is discussed. Finally, limitations of the studies included in this dissertation and avenues for future research are addressed.

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# CHAPTER 1

## Introduction

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## 1. A brief introduction into consciousness research

"Anything that we are aware of at a given moment forms part of our consciousness, making conscious experience at once the most familiar and most mysterious aspect of our lives."

(Susan Schneider & Max Velmans, 2008)

The question of the processes underlying the conscious perception of the stimuli surrounding us has concerned researchers since the formation of the psychological science in the 19<sup>th</sup> century (Frith & Rees, 2017). While the investigation of mental processes came to a halt in the behaviorist era, the *science of consciousness* (Velmans, 1993) saw a rapid rise in research activity since the 1990ies (Seth, 2018).

An important first step to make the underpinnings of human consciousness examinable is an operationalization of the construct. Unfortunately, no unanimous definition of consciousness exists (Chalmers, 2017; Cohen et al., 2012). Two key components can be distinguished: the level of consciousness (i.e., *wakefulness*) and the contents of consciousness (i.e., *awareness*) (Laureys, 2005; Zhao et al., 2019). Following a popular taxonomy (Block, 1995, 2007), regarding the contents of consciousness it is often differentiated between *access consciousness* and *phenomenal consciousness*. While access consciousness incorporates all verbally accessible stimulus representations that are available for higher-order processing at a given moment, phenomenal consciousness was established as a broader concept: "Phenomenal consciousness is experience; the phenomenally conscious aspect of a state is what it is like to be in that state. The mark of access-consciousness, by contrast, is availability for use in reasoning and rationally guiding speech and action." (Block, 1995, p. 1). The *qualia* aspect of phenomenal consciousness – meaning the subjective, emotional quality of perceived stimuli – is thought to be not (completely) verbally accessible and has been labeled as the "*hard problem*" of consciousness research (Chalmers, 1995; Crick & Koch, 2003). The question whether what a person can verbally express is simply a fragment of all contents of consciousness (Usher

et al., 2018; Wang et al., 2021), or if in contrast access consciousness “is all there is to consciousness” ((Naccache, 2018), p. 8; (Ward, 2018)) has been subject to a lively, and ongoing, debate (Overgaard, 2018; Phillips, 2018). Agreement seems to exist regarding the notion that access consciousness can be investigated with the methods of neuroscience, which constitutes the so-called “*easy problem*” according to Chalmers (1995). To date, assessing verbal report and contrasting neural activity between perceived and not perceived stimuli is the key methodological approach in consciousness research (Aru et al., 2012; Baars, 2017; Dehaene & Naccache, 2001; Overgaard, 2017). However, the reliance on introspection is not undisputed (Lamme, 2010; Pitts et al., 2018).

A primary goal of the neuroscientific investigation of consciousness is the identification of *neural correlates of consciousness* (NCCs) (Koch et al., 2016). NCCs can be defined as the necessary and sufficient set of neural processes underlying conscious experiences (Crick & Koch, 2003) – either in their entirety (“full NCC”) or regarding a specific stimulus (“content-specific NCC”) (Koch et al., 2016). Searching for consistent neural markers of conscious perception is not only of high scientific but also of high clinical interest. For example, established NCCs would allow an accurate identification of and differentiation between different levels of consciousness, such as minimally conscious state or coma (Laureys, 2005). Several candidates for NCCs have been proposed, for example the late event-related potential (ERP) P3 (Dehaene, 2014) or a “posterior hot zone” (Koch, 2018), but to date no consensus has been reached (Aru & Bachmann, 2015; Mashour, 2018; Overgaard, 2017). Sections 5 to 7 of this chapter will provide short reviews of some electrophysiological findings regarding NCCs in visual, auditory and cross-modal settings.

An essential prerequisite for the ongoing search for NCCs are suitable experimental paradigms. Most widely used are paradigms that allow a direct contrast of neural activity accompanying processing of perceived (i.e., *hit*) and not perceived (i.e., *miss*) stimuli under identical sensory stimulation (Aru et al., 2012; Rees & Frith, 2017). One experimental set-up suitable for this contrastive approach is the *distractor-induced blindness* (DIB) paradigm,

which is applied throughout all studies of this dissertation and will be introduced in the following section 2. This dissertation aims to adapt the DIB paradigm to auditory and cross-modal settings for the first time and to assess the influence of distractors on target processing within these settings. Examining electrophysiological correlates of access to an auditory target constitutes the second main subject of this dissertation.

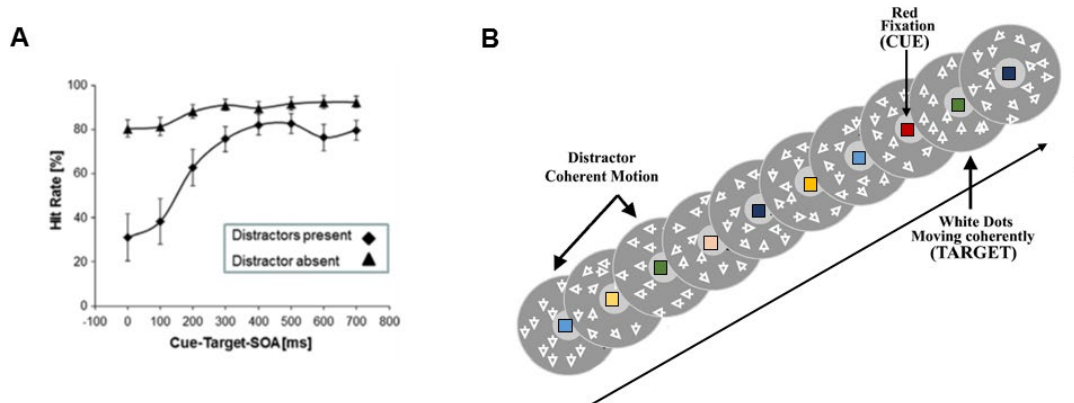
## 2. Distractor-induced blindness (DIB)

In the distractor-induced blindness (DIB) task, access to a target stimulus can be manipulated by the presentation of irrelevant events prior to the target. Since an adaptation of this task is used throughout this dissertation, the original visual paradigm as well as main behavioral and electrophysiological findings are described in this section.

The DIB paradigm, which was originally introduced as ‘attention induced motion blindness’ by Sahraie et al. (2001), contains two rapid serial visual presentation (RSVP) streams that are presented concurrently (see Figure 1B). One stream typically consists of the fixation at the center of the screen changing its color every 100 ms. If the fixation turns red (duration: 100 ms), this event is labeled as *cue*. In the other RSVP stream, a *random dot kinematogram* with a 10 Hz presentation rate is displayed. This kinematogram can contain short episodes of coherent motion of the dots (duration: 100 ms). The participant’s task is to decide after each trial whether an episode of coherent motion appeared with or shortly after the cue (yes/no). Such a task-relevant event is labeled the *target*. Cue and target can appear no more than one time per trial. Importantly, episodes of coherent motion can also occur before the cue – these *distractors* shall explicitly be ignored. Responses are usually non-speeded, given after the end of the trial and participants are instructed to respond as accurately as possible.

## Figure 1

## Distractor-induced blindness paradigm



*Note.* A) Rate of correct detection of the motion target (in %, y-axis) observed by Sahraie et al. (2001) as a function of cue-target-SOA (x-axis). Hit rates were reduced at short cue-target-SOAs, if multiple distractors were presented before the cue (black rectangles). This effect was not found in the absence of distractors (black triangles). Figure adapted from Niedeggen et al. (2015). B) Depiction of the DIB task. A cue was defined as the onset of a red fixation within a sequence of color changes of the fixation. A target could appear within the second RSVP stream, consisting of a random dot kinematogram. Short episodes of coherent motion of the dots were the target event, if they appeared simultaneously to or after the cue. Episodes of coherent motion before the cue should be ignored (i.e., distractors). Figure adapted from Niedeggen et al. (2002).

With this paradigm, it was demonstrated that multiple preceding distractors lead to a transient “blindness” for the target in a proportion of trials (Michael et al., 2011; Sahraie et al., 2001) (see Figure 1A). Several behavioral characteristics of DIB have been established: (1) distractors need to share the target’s feature in order to reduce probability of target detection (Michael et al., 2011; Niedeggen et al., 2012). DIB has been demonstrated not only for the target feature coherent motion (Sahraie et al., 2001) but also for orientation (Michael et al., 2011; Michael et al., 2012) and color changes (Winther & Niedeggen, 2017a). (2) The effect is elicited by multiple distractors in a cumulative fashion, one distractor does not suffice (Hesselmann et al., 2006; Winther & Niedeggen, 2017b; Winther & Niedeggen, 2018). (3) Target detection is impaired the most if cue and target are presented simultaneously and gradually recovers until a cue-target *stimulus onset asynchrony* (SOA) of approximately 300 ms (Michael et al., 2012; Niedeggen et al., 2002; Sahraie et al., 2001).



The DIB task has been combined with the measurement of event-related potentials (ERPs) to investigate visual NCCs. ERPs are extracted from the electroencephalogram (EEG) and provide a continuous, online measurement of stimulus processing with high temporal resolution (Luck, 2005). The assessment of ERPs constitutes a key neuroscientific method. Since ERPs are applied as a main method in this dissertation (Chapters 3 & 4), previous findings will be reviewed focusing solely on electrophysiological results.

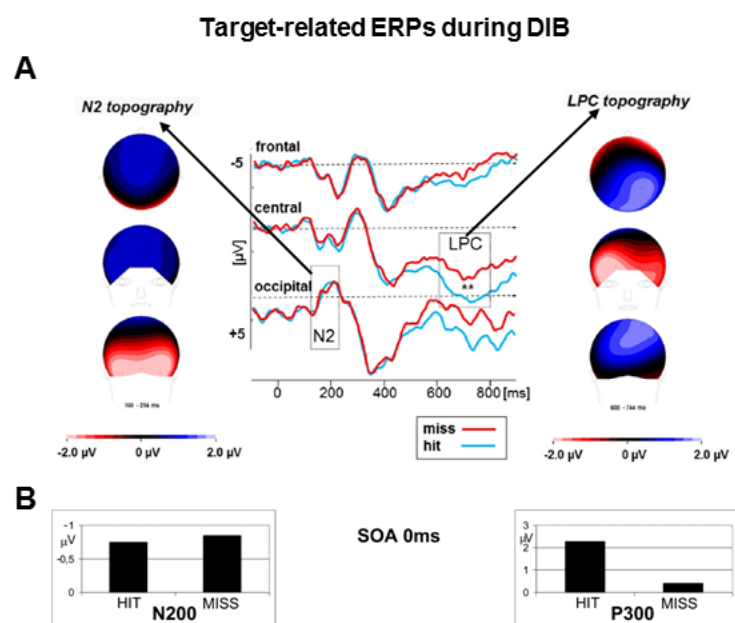
The experimentally evocable deficit in target detection in the DIB task enables an assessment of ERP signatures of target access under identical sensory stimulation. Previous ERP studies revealed that processing of hits and misses did not differ in early ERPs such as the occipital N2, indicating that sensory suppression cannot account for the effect (Niedeggen et al., 2015; Niedeggen et al., 2012; Niedeggen et al., 2002). Importantly, a late centro-parietal positivity (P3, P300) was found to be significantly more pronounced if the target was detected than if it was missed (Niedeggen et al., 2015; Niedeggen et al., 2002). Consequently, visual target awareness during DIB has been associated with a late, high-level process. The results of the ERP studies are illustrated in Figure 2. The P3 usually appears within 300 – 500 ms after stimulus onset and has often been linked to working memory processes (Polich, 2007) such as working memory updating (Donchin, 1981) and the inter-areal communication associated with this stimulus updating (Soto & Silvanto, 2014). Furthermore, the P3 component has been proposed as a possible signature of stimulus awareness (Dehaene et al., 2011; Naccache et al., 2016). The reduced late P3 for missed targets could be interpreted as depicting a temporary deficit in the activation of inter-areal communication processes. This temporary deficit may be caused by an inhibitory process driven by the distractors, resulting in a lack of conscious accessibility of the target (Niedeggen et al., 2015).

Extensive research in the visual modality has identified the behavioral and electrophysiological characteristics of distractor-induced blindness. However, at the start of this dissertation no studies existed that investigated a possible transferability of these

findings to different sensory modalities. This thesis aimed to close this research gap by examining DIB in the auditory modality, as well as under cross-modal (i.e., auditory-visual) stimulation. If similar behavioral characteristics can be observed outside of the visual modality, the mechanisms underlying DIB are not modality-specific, but apply across sensory modalities. The proposed model behind distractor-induced blindness and underlying important concepts and theories regarding top-down selective attention will be set out in the following section. Additionally, section 3 will address the relationship between attention and awareness.

**Figure 2**

*ERPs elicited by hits and misses in the visual DIB task*



*Note.* A) Grand-averaged ERP waves for the direct contrast between detected targets (blue line) and missed targets (red line) at frontal, central and occipital electrodes. No difference in an occipital N2 wave (160 – 200 ms, left side) was observed. Hits showed a significantly larger centro-parietal positivity (600 – 800 ms, right side), labeled here as late positive component (LPC). Figure adapted from Niedeggen et al. (2015). B) Mean of the grand averaged ERPs, presented separately for hits and misses, for an early negativity (N200; 160 - 240 ms) at the parietal electrode P3, and a late positivity (P300; 400-480 ms) at the parietal electrode P4. No differences were obtained for the N2, while hits were associated with a larger P300 than misses. Figure adapted from Niedeggen et al. (2002).

### 3. Attentional selection and inhibition during distractor-induced blindness

The phenomenon of distractor-induced blindness shows that multiple distractors, which share the target's features and are presented in advance of the relevant stimulus, hinder conscious perception of the target. The explanatory model proposed for DIB supposes a cumulative activation of a *negative attentional set* by the repeated presentation of target-like but task-irrelevant distractors (Niedeggen et al., 2015; Niedeggen et al., 2004; Niedeggen et al., 2012).

Stimuli can draw selective attention in a *bottom-up* or a *top-down* manner. Selective attention can be defined as the process of selecting a part of the incoming stimuli by enhancing the processing of some information and/or by suppressing other stimuli to ensure an efficient action and cognitive control as well as access to consciousness (Krummenacher & Müller, 2017; Theeuwes, 1993). Bottom-up attentional selection is exogenous and driven by stimulus features, especially physical stimulus saliency, in a rather automatic fashion (Nani et al., 2019; Theeuwes, 1992, 1993, 2010). In contrast, top-down attention is endogenous, voluntarily, and filters incoming information based on current task goals (Nani et al., 2019; Theeuwes, 2010). This goal-driven filter mechanism relies on *attentional sets* to optimize task performance (Dombrowe et al., 2011; Leber & Egeth, 2006; Olivers & Meeter, 2008; Wu & Fu, 2017; Zhang et al., 2009). An attentional set can contain a target feature (e.g., target color), leading to an attentional enhancement for stimuli possessing this target feature (Collins et al., 2010; Dombrowe et al., 2011; Drew et al., 2009). Besides such *positive attentional sets* or *target templates*, properties of distracting, task-irrelevant stimuli can be stored in *negative attentional sets*. These *distractor templates* can inhibit attentional selection of stimuli exhibiting distractor features (Arita et al., 2012; Olivers & Watson, 2006; Zhang et al., 2009, 2011).

DIB demonstrates that if features are shared between distracting and task-relevant stimuli, top-down inhibition of these shared features elicited by the repeated appearance of distractors can cause an involuntary suppression of processing of the subsequent target.

(Lleras et al., 2008; Moher et al., 2014; Niedeggen et al., 2012; Olivers & Watson, 2006). Consequently, target access can be impaired. This assumption of a top-down inhibition is in line with the *Boost and Bounce Theory of Temporal Attention* (Olivers & Meeter, 2008). The boost and bounce theory summarizes the interplay between inhibitory and excitatory top-down attentional processes in a RSVP task. Olivers and Meeter (2008) suggested that attentional sets work as a gating system into working memory, aiming to enhance relevant and to inhibit irrelevant information. Attentional sets comprise broader classes or categories (e.g., “colored”), so that the gating system can work as economical and as flexible as possible. This gating is assumed to work automatically after attentional sets are established based on task instructions. Stimuli that match the target template receive an attentional *boost*, while irrelevant stimuli are *bounced* by the gating system and thus prevented from entering working memory. In line with other two-phase models of temporal processing (e.g., (Chun & Potter, 1995)), Olivers and Meeter (2008) assume a first stage of sensory processing of stimulus features (including semantical and categorical information), followed by a second working memory stage. In working memory, attentional sets based on task demands are stored and stimulus representations are linked to responses, which makes a stimulus verbally reportable (Olivers & Meeter, 2008). The enhanced late positivity for hits during DIB (Niedeggen et al., 2015; Niedeggen et al., 2002) might be linked to the successful completion of this second stage.

Within the DIB model, the cue is assumed to function as a release signal that triggers the deactivation of the negative attention set (Michael et al., 2011). This release seems to happen gradually (Zhang et al., 2009) and target detection is fully recovered after 300 – 400 ms (Sahraie et al., 2001). A frontal negativity between 250 and 500 ms was found as electrophysiological correlate of the central inhibition (Niedeggen et al., 2015; Niedeggen et al., 2004; Niedeggen et al., 2012; Winther & Niedeggen, 2017a; Zhang et al., 2009). This distractor-evoked ERP component showed a gradual increase with increasing number of distractors, exclusively in trials in which the target was missed (Niedeggen et al., 2015). In

accordance with the inhibitory account, strong individual inhibition ability, as measured with the Stroop task, has been associated with a larger DIB effect (Milders et al., 2004).

The influence of attentional sets on target perception has also been examined under the related phenomenon of *Contingent Attentional Capture* (CAC; (Folk et al., 1992)). CAC demonstrates that if a target and a distractor stimulus share spatial or object-based features, the distractor can impair detection of the subsequent target (Folk et al., 2008; Folk & Remington, 1998; Ghorashi et al., 2003; Lien et al., 2008; Luck et al., 2021; Wu & Fu, 2017; Zhang et al., 2009). Importantly and in contrast to DIB, where multiple distractors are necessary to impair target access, for CAC the effects of a singleton distractor on response times or target perception are regarded.

The top-down allocation of selective attention and the inhibition of this attentional allocation are crucial mechanisms underlying stimulus access to consciousness, as demonstrated by DIB. While consciousness and attention have sometimes been regarded as inseparable, intertwined processes (De Brigard & Prinz, 2010; Posner, 1994), most recent research describes them as distinct – but closely related – mechanisms (Cohen & Chun, 2017; Dehaene et al., 2006; Koch & Tsuchiya, 2007; Lamme, 2003; Maier & Tsuchiya, 2021; Martín-Signes et al., 2019; Nani et al., 2019; Van Boxtel et al., 2010). Within this close relation, selective attention has often been proposed as a necessary but not sufficient condition for stimulus awareness ((Cohen et al., 2012; Cohen & Chun, 2017; Dehaene et al., 2006; Jensen et al., 2011; Pitts et al., 2018; Simons & Rensink, 2005), but see (Maier & Tsuchiya, 2021; Tsuchiya & Koch, 2014)). Phenomena like inattention blindness, change blindness or the attentional blink, which are described in section 5, show impressively that salient, supraliminal stimuli can go unnoticed if they are unattended, or if attentional limitations are reached (Cohen & Chun, 2017).

The next section will introduce two neuroscientific theories of consciousness and the different predictions regarding NCCs that can be derived from them. These theories provide

a framework in which findings concerning electrophysiological signatures, such as the observation of a late correlate of target perception during DIB, can be interpreted.

#### 4. Overarching theories of consciousness

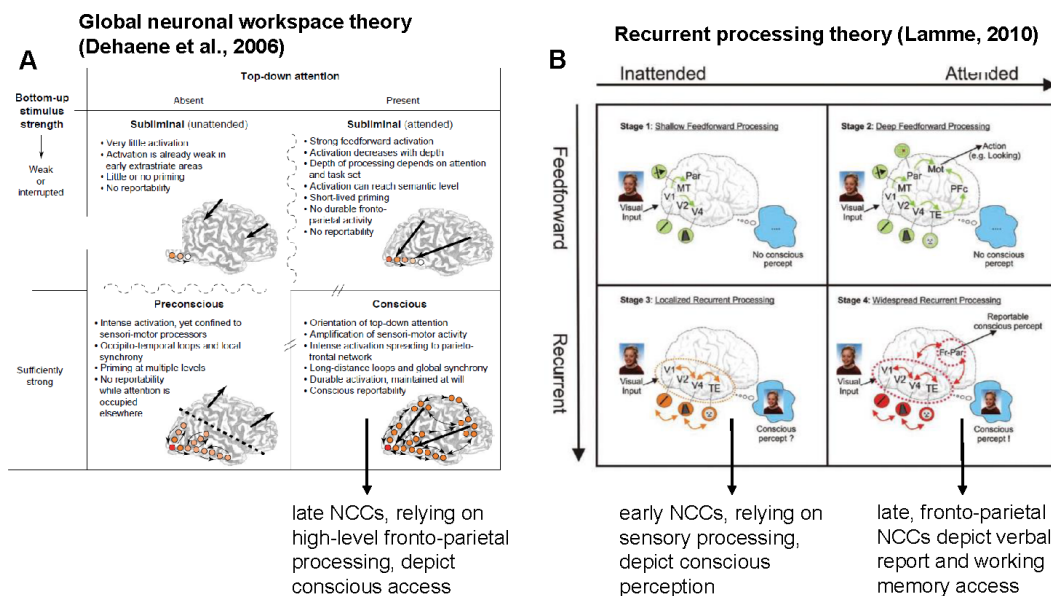
With the rise of research on the topic of consciousness and NCCs, several theories have been put forward, which aim to explain how and when awareness arises, while incorporating neuroscientific findings. Theories of consciousness differ in their assumption which neural processes underlie awareness. Some of these theories propose that consciousness depends on higher-order cognitive processes located in prefrontal and parietal areas (i.e., global neuronal workspace theory, higher-order theories). Other theories like the recurrent processing theory or the integrated information theory suggest that consciousness already arises earlier and that sensory processing and therefore sensory areas are the basis of awareness (for an overview: (Block, 2019; Morales & Lau, 2020)). In the following, two famous theories and their key assumptions will exemplarily be presented. One of these theories advocates for the importance of early, low-level processing and the other for a crucial role of late, high-level processing for awareness. Figure 3 illustrates the assumed stages of cortical processing and their relation to attention according to these two theories. It is important to note that the focus of all theories of consciousness lies heavily on the visual modality, both in their assumptions as well as in their experimental testing.

One influential theory suggesting a crucial role of fronto-parietal brain areas for conscious access is the *Global Neuronal Workspace Theory* (GNWT) (Baars, 1997, 2017; Dehaene et al., 2011). The GNWT postulates that conscious processing is characterized by a global broadcasting of neuronal activity involving higher-order association cortices connected by long-distance neurons (Dehaene et al., 2006). To reach this widespread 'global workspace', stimuli compete in an 'all-or-none'-fashion for reaching a certain threshold of activation first, which then leads to the ignition of the workspace for the 'winning' stimulus (Dehaene & Naccache, 2001; Morales & Lau, 2020). Being broadcasted in the global

workspace makes the stimulus representation available for report and cognitive control (Dehaene et al., 2017; Morales & Lau, 2020). If a stimulus fails to activate the global workspace, it remains unconscious. According to this theory (see Figure 3A), early sensory activation as well as selective attention are necessary but not sufficient for awareness (Dehaene et al., 2006) and NCCs should be located in fronto-parietal areas (Dehaene & Changeux, 2011). In line with this, a NCC of stimulus access suggested by GNWT-proponents is the late, parietal ERP component P3 (Dehaene et al., 2011; Mashour et al., 2020; Sergent et al., 2005). As outlined in section 2, this late NCC has been observed during DIB (Niedeggen et al., 2015).

**Figure 3**

*Illustration of central assumptions of the GNWT and RPT*



*Note.* A) Brain states according to the Global Neuronal Workspace theory. Whether a stimulus reaches access consciousness according to GNWT depends on a sufficient bottom-up stimulus strength and the orientation of top-down attention to the stimulus. The theory proposes late, fronto-parietal NCCs of consciousness, which depict global availability of the information. Figure adapted from Dehaene et al. (2006). B) Stages of processing as suggested by the Recurrent Processing theory. RPT postulates that conscious experience arises from recurrent processing in sensory areas, which should be depicted by relatively early NCCs deriving from these areas. Fronto-parietal activation is regarded as necessary for report and working memory access but not for conscious perception per se. Figure adapted from Lamme (2010).

While GNWT focusses on a higher-order fronto-parietal network and on access consciousness, one theory emphasizing the importance of posterior areas for visual awareness is the *Recurrent Processing Theory* (RPT) (Lamme, 2006, 2010). According to RPT (see Figure 3B), in a first, unconscious stage, visual signals are processed locally in primary visual areas in the occipital lobe. If the stimulus is attended, it is rapidly transferred alongside the visual pathways to higher-level prefrontal and motor areas in a 'feedforward sweep' (Lamme, 2010; Morales & Lau, 2020). In a next stage, information is exchanged within and between higher- and lower level visual areas via horizontal and feedback connections (i.e., 'localized recurrent processing') (Lamme, 2010). This stage is supposedly necessary and sufficient for (phenomenal) conscious perception (Lamme, 2006; Wu, 2018). Additionally, Lamme (2010) suggests a subsequent stage, in which recurrent processing becomes widespread and involves fronto-parietal cortices, enabling working memory access and verbal report of the stimulus. This last stage is in line with the GNWT. The RPT account assumes that true NCCs in the visual modality should occur relatively early in posterior, sensory areas (Lamme, 2010). In line with this assumption, a potential early correlate of visual awareness, supposedly originating in visual cortex, has been proposed as *visual awareness negativity* (VAN) (Förster et al., 2020; Koivisto & Revonsuo, 2010). This VAN, occurring around 200 ms after stimulus onset, was defined as difference wave between "aware" and "unaware" trials (Koivisto & Revonsuo, 2010).

The question when and where in the brain consciousness arises can only be answered using neuroscientific methods, such as ERPs, in combination with suitable experimental paradigms. In the following section, three paradigms related to DIB, which are often applied in consciousness research, are introduced. I will shortly review findings regarding electrophysiological NCCs in the visual modality acquired with these paradigms and relate these findings to the ERP results for DIB.



## 5. The search for visual neural correlates of consciousness

As stated in section 1, paradigms that allow a direct contrast between neural activity evoked by perceived stimuli (*hits*) and unconscious processing (*misses*) are a principal methodological approach in the search for NCCs (Baars, 2017; Kim & Blake, 2005; Rees & Frith, 2017; Rees et al., 2002). In the following, I will briefly introduce change blindness, inattention blindness and the attentional blink. These paradigms are presented here since likewise DIB, they comprise a transient “blindness” to relevant events and therefore enable a comparison between hits and misses under identical sensory stimulation (for an overview over other established experimental approaches like binocular rivalry or backwards masking see (Kim & Blake, 2005; Rees & Frith, 2017)). After the behavioral phenomena are described, findings regarding electrophysiological NCCs in the visual modality using these paradigms will be outlined.

Two striking phenomena that illustrate the close relation between attention and awareness are change blindness (CB) and inattention blindness (IB) (Jensen et al., 2011). *Change blindness* (Rensink et al., 1997) describes a failure to detect a change between two alternating images, if perceptual continuity is briefly interrupted (Cohen & Chun, 2017; Jensen et al., 2011; Simons, 2000; Simons & Rensink, 2005). Importantly, in the CB paradigm subjects are actively looking for changes and the change becomes easily visible if attention is directed directly to the location of the change (Jensen et al., 2011). *Inattention blindness* (Simons & Chabris, 1999) shows that when observers are engaged in an attention-demanding primary task (e.g., counting the basketball passes of one team), an unexpected, but very salient event (e.g., moonwalking gorilla among the basketball players) is often missed (see also (Most et al., 2001; Neisser & Becklen, 1975; Rock et al., 1992)). The failure of detecting unexpected stimuli has important practical implications, for example as a potential cause of driving accidents (Horrey & Wickens, 2006) or of errors in medical screenings (Drew et al., 2013). An experimental limitation of IB is that usually only one critical

trial per subject can be used since IB vanishes if subjects are alerted that unexpected events can occur (Cohen & Chun, 2017).

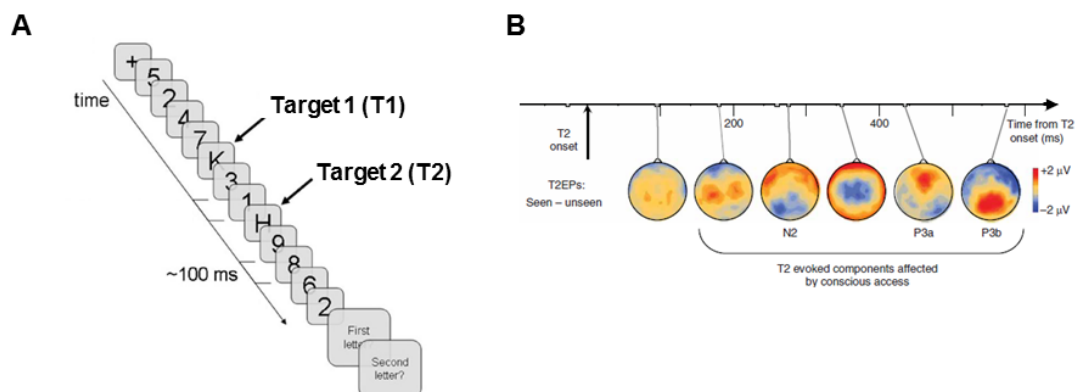
Using the change blindness paradigm, ERP studies consistently reported a reduced or completely suppressed P3 for undetected compared to detected changes (Busch et al., 2010; Koivisto & Revonsuo, 2003; Niedeggen et al., 2001; Schankin & Wascher, 2007; Scrivener et al., 2019; Turatto, Angrilli, et al., 2002). In addition, some of these studies also found an earlier correlate of change detection – a posterior negativity around 200 ms that showed larger amplitudes for detected changes (Busch et al., 2010; Koivisto & Revonsuo, 2003; Schankin & Wascher, 2007; Scrivener et al., 2019). For inattention blindness, a negative wave with parieto-occipital topography preceding the P3 was present only when subjects were aware of the critical stimulus (Pitts et al., 2011; Schelonka et al., 2017; Shafto & Pitts, 2015). Interestingly, this early negativity was only succeeded by a P3 wave, if the stimulus was task relevant (Schelonka et al., 2017; Shafto & Pitts, 2015). In a recent IB study, Schlossmacher et al. (2020) solely found an early posterior negativity – but not P3 – to be linked to conscious processing.

A well-established dual-task paradigm that demonstrates a temporary deficit in accessing a target stimulus is the *attentional blink* (AB) (Dux & Marois, 2009; Martens & Wyble, 2010; Raymond et al., 1992). The AB task consists of one RSVP stream, in which two targets are embedded (i.e., T1, T2) and should be detected (see Figure 4A). If the second target T2 appears within 200 – 500 ms after T1, it is often “blinked” and cannot be reported (Shapiro et al., 1997). Interestingly, T2 is usually detected if it follows directly after T1, which is labeled *lag 1 sparing* (Dux & Marois, 2009). Despite many similarities between AB and DIB, e.g. regarding the use of an RSVP task and the presentation of two task-relevant stimuli, some important differences have to be considered. These differences apply to the time course, with DIB being most expressed at a cue-target-SOA of 0 ms, as well as to the presentation of two and not one RSVP streams during DIB. Furthermore, they differ regarding their reliance on distractors. While DIB critically depends on the number of

distractors, requiring the presence of several distractors for the effect to occur, this does not seem to be the case for the AB (Zhang et al., 2009, 2011). The AB has often been attributed to attentional capacity limitations, proposing that T1 still occupies a capacity-limited second stage of processing necessary for working memory consolidation. If T2 is presented shortly afterwards, this leaves the initial representation of T2 susceptible to decay or overwriting (Chun & Potter, 1995; Dux et al., 2006; Dux & Marois, 2009; Jolicoeur & Dell'Acqua, 1998). Alternatively, *disrupted-engagement theories* (Nieuwenstein et al., 2005; Olivers & Meeter, 2008; Wyble et al., 2009) like the boost and bounce theory suggest a central role of top-down attentional control processes for the effect, with a reduced and delayed attentional enhancement of T2 taking place.

**Figure 4**

*Attentional blink task and ERPs for detected vs. missed targets (Sergent et al., 2005)*



*Note.* A) Depiction of the classic AB task. Figure adapted from Martens & Wyble (2010). B) Voltage maps for the difference between ERPs for perceived vs. not perceived T2s during the attentional blink (i.e., short T1-T2-SOA) in the study of Sergent et al. (2005). Following intact early potentials (N1, P1), the first large difference was observed in a posterior N2 wave, which was more pronounced for hits. A frontal (P3a) and posterior P3 component was only observed for perceived targets. Figure adapted from Sergent et al. (2005).

For the attentional blink, ERP studies showed a suppression and delay of the centro-parietal P3 wave in response to T2 within the typical AB window (i.e., short T1-T2-SOA) (Dell'Acqua et al., 2015; Dell'Acqua et al., 2003; Vogel & Luck, 2002; Vogel et al., 1998). Sergent et al. (2005) directly compared ERPs for detected and missed T2s and found that

the P3 was only present for hits. Furthermore, while no differences in early sensory processing were observed (i.e., intact N1, P1 waves), hit processing diverged from miss processing starting around 270 ms with a larger posterior N2 wave for detected targets (Sergent et al., 2005) (see Figure 4B). In line with this, a recent ERP review for the visual AB (Zivony & Lamy, 2021) suggested an early and a late signature of T2 identification: the posterior N2 – supposedly reflecting attentional enhancement – and the subsequent P3 as index of working memory encoding. These findings fit well within the disrupted-engagement theories of the AB (Nieuwenstein et al., 2005; Olivers & Meeter, 2008; Wyble et al., 2009). These theories assume that attentional enhancement of T2 is disrupted during the AB, making working memory encoding and thus conscious access of the not sufficiently activated T2 less likely (Zivony & Lamy, 2021).

To sum up, the majority of electrophysiological findings using the discussed paradigms indicated that visual target access is linked to a posterior negativity occurring around 200 ms after target onset (N2; VAN) and/or a later, centro-parietal positivity (P3). Importantly, with the DIB paradigm, no early, but solely a late ERP correlate of visual target access has been observed (Niedeggen et al., 2015; Niedeggen et al., 2002). Some researchers propose that visual consciousness is depicted by the VAN occurring around 200 ms after target onset (Förster et al., 2020; Koch et al., 2016; Koivisto et al., 2016; Mazzi et al., 2020; Schlossmacher et al., 2020), while the P3 reflects post-perceptual processes linked to response behavior and decision making (Cohen et al., 2020; Pitts et al., 2014; Schröder et al., 2021; Verleger, 2020). This assumption is in line with ‘early’ theories like the RPT, which assume a strong link between awareness and sensory processing (Lamme, 2006). On the contrary, others suggest that consciousness perception develops rather late and is reliably indicated by the P3 (Babiloni et al., 2005; Boncompagni & Cosmelli, 2018; Dehaene et al., 2011; Naccache et al., 2016; Niedeggen et al., 2015; Rohaut & Naccache, 2017; Salti et al., 2012), as proposed by the GNWT theory. Integrating both accounts, it has been put forward that VAN and P3 might be both valid correlates of visual awareness, which each reflect a

different stage of conscious processing (Derda et al., 2019; Filimonov et al., 2022; Rutiku et al., 2015; Ye et al., 2019).

Consciousness research has focused largely on vision. Three times more studies regarding visual than auditory consciousness were conducted until 2015 and only few studies used multisensory stimuli (Faivre et al., 2017). Consequently, the mechanisms behind conscious auditory - and even more so cross-modal - perception are less well understood. This raises the question whether the correlates of awareness observed within the visual modality are specific to vision or whether they are transferable to other sensory modalities and thus depict general markers of consciousness. Since this dissertation aims to adapt the visual DIB paradigm to auditory and auditory-visual settings, it is important to consider particularities of auditory and multisensory processing. In the following section, differences between visual and auditory processing as well as behavioral and electrophysiological findings for AB, CB and IB within the auditory modality are outlined.

## **6. Auditory processing and correlates of auditory awareness**

While a reliable distractor effect on target detection has been established in vision, the DIB paradigm has never been applied in a different sensory modality, raising the question of the transferability of the effect to auditory stimuli. As summarized in section 3, DIB has been explained based on the role of top-down filtering processes of attention (Niedeggen et al., 2015; Niedeggen et al., 2012; Olivers & Meeter, 2008). Not only visual but also auditory perception relies heavily on goal-driven attentional sets (Dalton & Lavie, 2007; Joos et al., 2014; Mast et al., 2017; Sussman et al., 2002). This could indicate that the same top-down attentional mechanisms apply, which may speak for a transferability of the distractor effect to audition. However, some fundamental differences between both sensory modalities need to be considered.

Several differences between visual and auditory stimulus processing can be stated: First, the auditory system is characterized by a higher temporal integration of incoming

information compared to the visual system (Grahn, 2012; VanRullen et al., 2014). Auditory input changes rapidly and is often fleeting, whereas visual input is usually more stable in time, leading to the necessity of a higher temporal precision in auditory processing in terms of milliseconds in contrast to tens of milliseconds in vision (Grahn, 2012; Zoefel & VanRullen, 2017). The auditory system is assumed to dominate the visual system in the temporal domain, while the visual system can be dominant in spatial perception (Grahn, 2012). Second, auditory input receives a more extensive preprocessing by subcortical structures, while visual processing is predominantly cortical (VanRullen et al., 2014). Before reaching the primary visual cortex, visual input from the retina solely passes through one subcortical nucleus, the lateral geniculate nucleus (Müsseler, 2017). In contrast, auditory information passes through and is processed by several subcortical structures - the cochlear nucleus, superior olivary, inferior colliculi, and medial geniculate nucleus - between the cochlea and the primary auditory cortex (Bendixen & Schröger, 2017). Furthermore, perceptual load impacts the processing of distractors in vision (Lavie, 2010; Lavie & Tsal, 1994), while this effect can apparently not be stated consistently for auditory stimuli (Murphy et al., 2013; Murphy et al., 2017). It has been proposed that the auditory system might have additional processing capacity for unattended information, due to its function as an 'early warning' system (Dalton & Lavie, 2007; Murphy et al., 2013). The structural and functional differences between the two modalities suggest that visual phenomena cannot be automatically transferred to auditory stimuli.

While data for DIB outside of the visual modality are lacking, the related phenomena introduced in section 5 have been investigated within the auditory modality. Most studies examining the auditory attentional blink indicated the existence of an auditory effect (Duncan et al., 1997; Horváth & Burgyán, 2011; Shen & Alain, 2010; Shen et al., 2018; Tremblay et al., 2005; Vachon & Tremblay, 2006). However, some studies found that an auditory AB was absent (Koelewijn et al., 2008; Potter et al., 1998), or reduced compared to the visual effect (Arnell & Jenkins, 2004; Soto-Faraco & Spence, 2002). If an auditory blink was reported, it showed a different time course than the visual AB: during the auditory AB, a rather linear

increase in T2 detection with increasing T1-T2-SOA occurred (Shen & Alain, 2010). In contrast, the visual effect typically shows a “U-shaped” pattern for hit rates with T1-T2-SOA on the x-axis (Shapiro et al., 1997). Moreover, no lag 1 sparing - a consistently reported signature of the visual AB - was observed for auditory stimuli (Horváth & Burgyán, 2011; Vachon & Tremblay, 2005).

In line with visual findings, the few ERP studies investigating T2 processing during the auditory AB found a suppressed P3 component in response to T2, if T2 was presented within the window of the auditory blink (Finoia et al., 2015; Shen & Alain, 2010). Likewise, misses showed a reduced P3 compared to hits (Shen et al., 2018). Finoia et al. (2015) reported a reduced early central N2 within the AB window in addition to the P3 reduction. Interestingly, Shen and Alain (2010) also observed a reduced N1-P2-complex for T2, which suggested a reduction of sensory processing during the auditory attentional blink.

For change blindness and inattention blindness, a limited amount of research suggested that changes and unexpected events can also go unnoticed in the auditory modality, indicating *inattention deafness* (Dalton & Fraenkel, 2012; Sinnott et al., 2006), and *change deafness* (Dickerson & Gaston, 2014; Eramudugolla et al., 2005; Gregg & Samuel, 2008; Gregg & Snyder, 2012; Koreimann et al., 2014). Consequently, auditory findings for these effects related to DIB suggest that some visual phenomena can also be observed within the auditory modality, while modality-specific particularities might occur, as shown by the auditory AB.

Change deafness studies found that missed changes between two auditory scenes were accompanied by a smaller P3 component than detected changes (Gregg & Snyder, 2012; Puschmann et al., 2013). Additionally, the early sensory N1 was reduced (Gregg & Snyder, 2012; Puschmann et al., 2013) and Puschmann et al. (2013) found a diminished central N2 for misses. Using an inattention deafness task, Schlossmacher et al. (2021) observed a larger early anterior negativity for perceived vs. missed spoken words among distracting auditory stimuli, while the P3 only emerged for task relevant stimuli.

Recently, Eklund and Wiens (2019) suggested based on an auditory threshold detection task that auditory awareness is indicated by both an early *auditory awareness negativity* (AAN) in analogy to the visual VAN and by the late P3 component. The AAN has been described as occurring after about 200 ms at fronto-central electrodes, showing a maximum contralateral to the target and supposedly originating in auditory cortices (Eklund et al., 2019, 2021; Wiegand & Gutschalk, 2012).

In conclusion, in both the auditory and visual domain, a similar debate regarding early vs. late electrophysiological correlates of awareness is in progress. Research in both modalities indicated that an early negativity and/or a late post-sensory positivity are the most promising ERP correlates of target access. The early negativity might possibly originate in the respective sensory cortices (Dembski et al., 2021) or reflect attentional processes (Zivony & Lamy, 2021). While an early correlate elicited in sensory cortices would be in line with recurrent processing accounts of consciousness (Lamme, 2010), the GNWT (Dehaene et al., 2011) assumes that the late P3 indicates 'global ignition' and therefore awareness. Reliable signatures of consciousness would be expected to also occur in cross-modal stimulus conditions, but to date, there is a lack of cross-modal studies contrasting the processing of hits and misses. In the next section, particularities of cross-modal processing and some of the sparse electrophysiological findings regarding NCCs of cross-modal awareness are briefly outlined.

## **7. Particularities of cross-modal processing**

Sensory stimulation can be restricted to one modality but in daily life, it is rather the rule than the exception that stimuli occur in different sensory channels and need to be concurrently filtered and processed (Koelewijn et al., 2010). Research on such *cross-modal* or *multisensory* processing showed that stimuli from different modalities often interact regarding the allocation of attention and the processing of the individual stimuli (Alais et al., 2010; Ghazanfar & Schroeder, 2006; Koelewijn et al., 2010; Talsma et al., 2010).



Multisensory research revealed that primary sensory cortices respond to sensory input from different sensory modalities (Kayser, 2010; Liang et al., 2013). This indicates that multisensory processing already starts at the sensory level and is not restricted to higher-order association areas (Ghazanfar & Schroeder, 2006). If sensory inputs from different modalities coincide in time and/or space, they are likely to be integrated into a unitary percept (Koelewijn et al., 2010; Talsma et al., 2010). This *multisensory integration* is often accompanied by *multisensory enhancement*, meaning an increased probability of correctly detecting the stimuli and of a faster response to them than in unimodal conditions (Stein & Stanford, 2008; Stevenson et al., 2014), especially if both stimuli are task relevant (Barutchu et al., 2013). Regarding attentional resources, it is subject of an ongoing debate whether a shared pool for all sensory modalities exists or if distinct attentional resources are available for each sensory modality (Wahn & König, 2017). The latter would result in larger attentional resources in cross-modal settings. A possible influence of multisensory enhancement effects for stimuli occurring in close temporal proximity and the potential availability of additional attentional resources could indicate that robust behavioral effects such as DIB might be diminished in cross-modal compared to unimodal settings.

The particularities of cross-modal processing raise the question whether the described deficits in detecting relevant stimuli observed in visual and occasionally also auditory modality (i.e., AB, CB, IB) occur in the same way in auditory-visual stimulus conditions. The AB has been predominantly studied within a single sensory modality (Wahn & König, 2017), and the relatively few studies combining visual and auditory stimulation came to inconclusive, heterogeneous results. Some researchers found an auditory-visual AB (Arnell, 2006; Arnell & Jenkins, 2004; Arnell & Jolicoeur, 1999; Arnell & Larson, 2002; Jolicoeur, 1999), while others reported the absence of such a cross-modal blink (Duncan et al., 1997; Finoia et al., 2015; Hein et al., 2006; Potter et al., 1998; Soto-Faraco & Spence, 2002; Van der Burg et al., 2007). If a cross-modal AB was detected, it was often smaller than unimodal effects (Arnell & Jenkins, 2004). These differences were attributed to a larger amount of available processing resources during the cross-modal AB since attentional

limitations are not reached within the individual modalities and only central limitations apply (Arnell & Jenkins, 2004).

For IB, the sparse cross-modal research conducted indicated that detection of an unexpected event can be impaired if a demanding primary task is performed in the other sensory modality (Macdonald & Lavie, 2011; Molloy et al., 2015; Raveh & Lavie, 2015; Sinnett et al., 2006). Importantly, all but one study (Sinnett et al., 2006) solely regarded the influence of visual task load on the detection of an auditory stimulus. Furthermore and in line with observations for the AB, Sinnett et al. (2006) found that IB was smaller in cross-modal compared to unimodal conditions, which was interpreted as an indicator of distinct attentional resources for each modality. To my knowledge, the Change Blindness paradigm has never been adapted to auditory-visual conditions – likewise the DIB paradigm. In summary, to date the question of transferability of the mentioned visual phenomena to auditory-visual settings cannot be conclusively answered and there are indications of diminished effects in cross-modal conditions.

So far, unimodal visual and auditory ERP research revealed an early (N2; VAN/AAN) and a late (P3) component as most promising potential correlate(s) of awareness. Can these signatures also be found in a cross-modal setting? Unfortunately, the number of cross-modal ERP studies is sparse and direct comparisons of hits and misses under auditory-visual stimulation are missing. The few auditory-visual AB studies have focused largely on the P3 and only regarded effects of T1-T2-SOA on ERPs. Within the typical AB window, a reduced or delayed P3 in response to targets was found (Arnell, 2006; Dell'Acqua et al., 2003; Ptito et al., 2008). It is important to note, however, that the P3 reduction was observed in both the absence and the presence of a cross-modal AB effect (Arnell, 2006; Ptito et al., 2008). In contrast, Finoia et al. (2015), who did not find a cross-modal AB, reported a preserved N2 and P3 component at short lags. Since none of these studies compared hit and miss processing, it remains unclear whether the early and late correlates described within visual

and auditory modality can also be observed in a cross-modal task. Study II (Chapter 4) will provide such a contrastive analysis using a cross-modal adaption of the DIB paradigm.

This dissertation wants to provide a contribution to auditory and cross-modal research by examining the DIB effect and electrophysiological NCCs of auditory target access within auditory and auditory-visual settings. In the following final section of this introduction, the research agenda behind this thesis is expounded.

## 8. Research Agenda

Two main aims are underlying this dissertation. The first aim is to experimentally validate an adaption of the DIB paradigm in auditory and cross-modal (i.e., visual - auditory) settings. Therefore, it is examined whether distractor stimuli, which share the features of a target, impair the conscious perception of the task-relevant stimulus in the auditory modality (Chapter 3), as well as in different cross-modal stimulus conditions (Chapters 4 & 5). The present work aims to transfer the visual paradigm to different sensory modalities for the first time. It shall be assessed whether a *distractor-induced deafness* (DID) can be stated and whether the behavioral characteristics of DIB can be observed under cross-modal stimulation. Due to the described particularities of auditory and cross-modal processing compared to visual processing, modality-specific differences in the distractor effect could be expected.

The second aim is to study ERP correlates of auditory target awareness in the auditory (Chapter 3) and cross-modal DID task (Chapter 4). It should be examined whether the late ERP correlate observed during visual DIB (Niedeggen et al., 2015) can also be consistently found outside of the visual modality and if auditory target access during DID also solely relies on a late, high-level process. The findings shall provide a contribution to the debate regarding early vs. late ERP signatures of auditory awareness and the ongoing search for reliable NCCs.

An outline of the research questions, hypotheses and of the method of the studies comprised in this dissertation follows in Chapter 2. In the final Chapter 6, the empirical findings reported in detail in Chapters 3 - 5 are discussed with regard to possible implications, limitations and avenues of future research.

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## CHAPTER 2

### Summary of the aims and research questions of this dissertation

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Following the overarching aims outlined in the introduction, this thesis consists of three consecutive empirical studies. Research objectives, hypotheses, as well as the general methodological approach of the individual studies will now be briefly introduced. Table 1 provides an overview of the experimental manipulations. The studies are described in detail in Chapters 3 – 5, which also each comprise illustrations of the respective experimental set-up. In all studies, the paradigm of distractor-induced blindness was applied and adapted to the auditory and cross-modal setting. A summary of experimental results is provided at the beginning of Chapter 6.

**Table 1**

*Overview of experimental manipulations in Studies I – III*

	<b>Study I (Chapter 3)</b>	<b>Study II (Chapter 4)</b>	<b>Study III (Chapter 5)</b>
<b>cue</b>	deviant tone (A)	small white circle (V)	Exp. 1: rise in amplitude (A) Exp. 2: deviant tone (A) Exp. 3: rise in amplitude (A)
<b>target</b>	rise in amplitude (A)	rise in amplitude (A)	Exp. 1: small white circle (V) Exp. 2: small white circle (V) Exp. 3: color change (V)
<b>independent variables</b>	cue-target SOA (0 vs. 300 ms) distractors (0 vs. 1 vs. 6-8) auditory presentation mode (superimposed vs. separate)	cue-target SOA (0 vs. 100 vs. 300 ms) distractors (0 vs. 1 vs. 6-8)	cue-target SOA (0 vs. 100 vs. 300 ms) distractors (0 vs. 1 vs. 6-8)
<b>dependent variables</b>	hit rate (%) ERPs elicited by target (multiple distractor condition)	hit rate (%) ERPs elicited by target (multiple distractor condition)	hit rate (%)

*Note.* “A” in parentheses indicates that this stimulus was auditory, while “V” indicates a visual stimulus. Distractors were always defined by the same feature as the target and were always presented in the same sensory modality.

**Study I:** *Can a distractor-induced deafness with the typical characteristics of DIB be found within the auditory modality? What are electrophysiological signatures of successful auditory target detection? (Chapter 3)*

Auditory research on phenomena related to DIB like the attentional blink showed that characteristics of a well-established visual effect do not necessarily translate to the auditory

modality (Horváth & Burgyán, 2011; Shen & Alain, 2010; Vachon & Tremblay, 2005).

Additionally, auditory and visual processing show functional and structural differences (see section 6 of Chapter 1). Research using the DIB paradigm has been restricted to the visual modality, which led to the research question whether the behavioral characteristics of DIB (see section 2 of Chapter 1) can also be observed for auditory stimuli. If distractors impair target detection in the auditory modality, *distractor-induced deafness* (DID) can be stated.

Previous studies have investigated ERP correlates of target detection during DIB by contrasting detected and missed targets. The main finding of these electrophysiological studies was that visual target awareness was solely linked to a late positivity (P3) (Niedeggen et al., 2015; Niedeggen et al., 2002). In extension of these previous studies, the second research question of Study I was which electrophysiological correlates accompany auditory target access during distractor-induced deafness.

To address both research questions, an auditory task with two synchronous rapid serial auditory presentations (RSAPs) in analogy to the visual DIB task was developed. One stream could contain a cue, the other stream distractor(s) and target. The first auditory stream consisted of a random sequence of pure sine-wave tones, in which a deviant tone (i.e., overlay of two tones) could be embedded as cue. The second stream contained a continuous tone. The target was defined in this second stream as a short rise in amplitude of the continuous tone appearing simultaneous to or shortly after the cue. Rises in amplitude occurring before cue onset should be ignored (i.e., distractors). In line with the original DIB task, participants had to decide after each trial whether they had perceived the cue (question 1) and the target (question 2) in a bimodal, non-speeded response mode (yes/no). In order to examine correlates of auditory target awareness, ERPs were measured and compared between hits and misses in the critical multiple distractor condition (cue-target-SOA: 0 ms).

Study I comprised a behavioral ( $N_{\text{final}} = 26$ ; 18 women; 18 — 47 years of age;  $M_{\text{age}} = 24.36$ ,  $SD = 7.38$ ) and a subsequent ERP experiment ( $N_{\text{final}} = 31$ ; 22 women; 18—43 years of age;  $M_{\text{age}} = 25.94$ ,  $SD = 7.11$ ). In both experiments, the number of distractors was

manipulated as within-subject variable (0 vs. 1 vs. 6-8 distractors) and the hit rate (correct target detection after correctly detected cue in %) was assessed as dependent variable. Additionally, in the behavioral experiment the cue-target-SOA (0 ms vs. 300 ms) as within-subject factor and the auditory presentation mode (separate vs. superimposed auditory streams) as between-subject factor were manipulated. The factor presentation mode was included to assess a possible effect of auditory segregation, with the auditory streams being presented separately to different ears in the separate stream condition and superimposed to both ears in the superimposed condition. In the ERP experiment, both auditory streams were always spatially separate and each presented to one ear. ERPs elicited by the cue-target-compound were acquired as second dependent variable in the ERP experiment.

The following two hypotheses were defined *a priori*:

- 1) Multiple distractors were expected to impair detection of the auditory target. The largest distractor effect was hypothesized to occur at a cue-target SOA of 0 ms. These findings would indicate a *distractor-induced deafness* (DID).
- 2) Regarding ERPs elicited by detected and missed targets it was expected that hits are accompanied by a larger P3 component than misses. If the P3 also indicates target access during DID, this would speak for the notion of the P3 being a reliable, universal signature of awareness (Dehaene, 2014).

**Study II:** *Is the distractor effect on target detection also observable if the cue is visual and the target auditory? Can the electrophysiological correlates of auditory target access observed in Study I be replicated in this cross-modal setting? (Chapter 4)*

Following the first investigation of distractor-induced deafness in Study I, it should subsequently be examined whether the distractor effect persists in a cross-modal setting. This cross-modal set-up was defined by the cue being presented in the visual domain and target and distractors being auditory stimuli. As outlined in section 7 of Chapter 1, previous research produced sparse and inconclusive results regarding the transferability of visual



effects to cross-modal set-ups. The second aim of Study II was to assess ERP signatures of auditory target access and, more specifically, to test whether the ERP correlates observed in Study I are also found if cue and target stem from different modalities.

To ensure comparability between auditory and cross-modal findings, the experimental set-up and the analysis procedure remained as similar as possible. While the two auditory streams and the target/distractor events were identical to Study I, a visual cue was now embedded in an additional RSVP sequence. The visual stream was displayed concurrently to the auditory sequences and consisted of a small circular arrangement of eight bars presented at the center of the screen. The impression of a clockwise motion, resembling a symbol indicating a loading process ('preloader' symbol), was created by varying the luminance between the adjacent greyscale bars. The cue was defined as the appearance of a small white circle with black outline at the position of one of the bars. In line with previous studies, the target could appear with or after the cue and target-like auditory stimuli preceding the cue (i.e., distractors) had to be ignored. Cue and target detection was again assessed after the end of each trial in bimodal (yes/no), non-speeded response mode.

Study II comprised a behavioral ( $N_{\text{final}} = 20$ ; 13 women; 18 — 39 years of age;  $M_{\text{age}} = 29.20$ ,  $SD = 5.92$ ) and an ERP experiment ( $N_{\text{final}} = 34$ ; 20 women; 19 — 34 years of age;  $M_{\text{age}} = 24.33$ ,  $SD = 4.99$ ). As in Study I, in both experiments the number of distractors (0 vs. 1 vs. 6-8) was manipulated as within-subject variable, while the target hit rate (in %) was measured as dependent variable. As second independent variable, the cue-target-SOA was manipulated in the behavioral experiment (0 ms vs. 100 ms vs. 300 ms). ERPs elicited by the cue-target-compound (multiple distractor condition, cue-target-SOA 0 ms) were assessed and contrasted between detected and missed targets.

The following two *a priori* formulated hypotheses were investigated:

- 1) Multiple auditory distractors, sharing the target's features, were expected to impair auditory target detection, irrespective of the cue as signal of task relevance now being defined in the visual modality. In line with the model proposed for DIB (see section 3 of

Chapter I), it was expected that a negative attentional set should be activated by the repeated presentation of distractors, leading to reduced target detection at short compared to longer cue-target SOAs.

2) The ERP signatures of auditory target access observed in Study I were expected to be replicated in this cross-modal setting if they constitute reliable signatures of auditory awareness. This comprised an early frontal negativity (FN) and the late, centro-parietal positivity (P3), which were hypothesized to both be enhanced for hits.

**Study III:** *Can DIB be found if the cue is auditory and the target visual? Is the distractor effect influenced by the feature defining the auditory cue? Does the visual target feature influence the cross-modal effect? (Chapter 5)*

In Study III, three research questions were examined in three successive behavioral experiments. First, it was assessed whether a cross-modal effect of multiple distractors on target detection can also be stated for visual targets indicated by an auditory cue, and therefore for reversed modalities as in Study II. The distractor effect should be most pronounced at cue-target-SOA of 0 ms and decrease with increasing SOA. This cross-modal effect should be compared to the behavioral experiment from Study II, in which the assignment of cue and target to sensory modalities was reversed, to assess modality-specific differences in the expression of the effect. Second, a potential impact of the auditory cue feature on this cross-modal effect was investigated. It should be tested if a transient increase in loudness is especially effective in redirecting attention to the target by comparing it to a deviance in frequency composition as cue. Third, two different visual features, the appearance of a small circle and a color change, were compared regarding their efficiency to elicit a cross-modal DIB effect. Previously, DIB was demonstrated for the features motion, orientation and color (Michael et al., 2011; Winther & Niedeggen, 2017a). It was shown that color distractors are especially efficient in eliciting feature inhibition (Winther & Niedeggen, 2018), indicating some amount of feature specificity for DIB. In this Study III, a fourth, new visual feature – the appearance of a small circle, associated with a local change in luminance – was tested for the first time and compared to the established feature color change.

With the aim of ensuring comparability between studies, as many aspects as possible regarding experimental procedure, manipulations, and stimulus material were inherited from Studies I and II. Both auditory streams were taken from my previous experiments, in combination with the concurrent visual RSVP stream applied in Study II. The cue was now always auditory (rise in amplitude in Exp. 1 & 3; overlay of two tones in Exp. 2) and target and distractors appeared in the visual stream (appearance of a small white circle in Exp. 1 & 2; color change in Exp. 3). While the visual stream was identical to Study II in Experiments 1 and 2, in Experiment 3 the 'preloader' symbol was colored in green and could briefly change to pink, depicting the target event if it appeared with or after the cue.

The samples of the three experiments were independent and did not include the same participants twice (Exp. 1:  $N_{\text{final}} = 18$ ; 13 women; 20 – 35 years of age;  $M_{\text{age}} = 25.61$ ,  $SD = 5.25$ ; Exp. 2:  $N_{\text{final}} = 20$ ; 11 women; 18 – 35 years of age;  $M_{\text{age}} = 25.59$ ,  $SD = 4.46$ ; Exp. 3:  $N_{\text{final}} = 18$ ; 13 women; 18 – 40 years of age;  $M_{\text{age}} = 27.65$ ,  $SD = 6.74$ ). The number of distractors (0 vs. 1 vs. 6-8) as well as the cue-target-SOA (0 ms vs. 100 ms vs. 300 ms) were manipulated as within-subject factors. Target hit rate was assessed as dependent variable.

The following hypotheses were examined:

- 1) Cross-modal distractor-induced blindness with the typical behavioral characteristics (i.e., effect of multiple distractors on target detection, largest target detection deficit at cue-target SOA 0 ms) was expected for an auditory cue and visual distractors/target.
- 2) If a transient increase in loudness is especially efficient in redirecting attention to the target, the distractor effect should be more expressed if the cue was a change in frequency composition.
- 3) If a larger cross-modal distractor effect is observed for the feature color than for the appearance of a small circle, this indicates that color is more efficient in activating the inhibitory process underlying DIB. Differences in the expression of cross-modal DIB for different target features would indicate feature specificity in this cross-modal setting.

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## CHAPTER 3

# Distractor-induced deafness: The effect of multiple auditory distractors on conscious target processing

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### Abstract

Conscious access to a target stimulus embedded in a rapid serial visual presentation can be impaired by the preceding presentation of multiple task-irrelevant distractors. While this phenomenon – labeled distractor-induced blindness (DIB) – is established in vision, it is unknown whether a similar effect can be observed in the auditory modality. Considering the differences in the processing of visual and auditory stimuli, modality-specific effects in the inhibitory mechanisms triggered by distractors can be expected. First, we aimed to find evidence for a distractor-induced deafness (DID) for auditory targets in a behavioral experiment. The target was defined by a transient increase in amplitude in a continuous sinusoidal tone, which was to be detected if accompanied or preceded by a deviant tone (cue). Both events were embedded in separate streams in a binaural rapid serial auditory presentation. Distractors preceded the cue and shared the target's features. As previously observed for DIB, a failure to detect the auditory target critically relied on the presentation of multiple distractor episodes. This DID effect was followed up in a subsequent event-related brain potentials (ERP) study to identify the signature of target detection. In contrast to missed targets, hits were characterized by a larger frontal negativity and by a more pronounced centro-parietal P3b wave. Whereas the latter process was also observed in the visual domain, indicating a post-perceptual updating process, the frontal negativity was exclusively observed for auditory DID. This modality-specific process might signal that early attentional control processes support conscious access to relevant auditory events.

**Keywords:** EEG, conscious access, inhibition, auditory processing, distractor-induced blindness

## 1. Introduction

In contrast to our rich environment, the verbally accessible contents of consciousness at a given time are limited (Baars, 1997; Block, 2007; Dehaene et al., 2011). Although theoretical accounts agree that stimuli compete for access to consciousness, the implementation and mechanism of the selection process is still debated.

Top-down models of attentional control emphasize that a pre-defined task defines the settings of a central filter (attentional set). The attentional set prioritizes stimuli based on simple feature characteristics, such as color or orientation (Leber & Egeth, 2006). Positive attentional sets enhance processing of stimuli with pre-defined features (Nieuwenstein, 2006; Raymond et al., 1995), whereas negative attentional sets lead to the inhibition of these stimuli (Olivers & Watson, 2006; Zhang et al., 2009). A negative attentional set might also be engaged in the suppression of task-irrelevant distractors in a rapid serial visual presentation (RSVP) task (Olivers & Meeter, 2008; Zhang et al., 2009), which can affect the probability for access to the target.

To assess the characteristics of inhibitory processes, several experimental paradigms have been developed. In this experiment, we use the distractor-induced blindness (DIB; (Michael et al., 2011; Sahraie et al., 2001)), which shares some characteristics with the established *Contingent Attentional Capture* (CAC; (Folk & Remington, 1998; Folk et al., 1992)) and the *Attentional Blink* (AB; (Raymond et al., 1992)). In CAC, a single distractor preceding the target affects response time. In AB, two targets are embedded in a RSVP stream and conscious access to the second target is restricted depending on the temporal distance to the first target. The distractor-induced blindness combines the properties of these paradigms: Two relevant events occur in two RSVP streams presented concurrently. A “local stream” (e.g., change of the color of fixation at 10 Hz) contains a cue (e.g., single onset of a red fixation). In a “global stream” (e.g., random dot kinematogram surrounding the fixation), the target event is defined (e.g., short coherent motion). Participants have to decide whether simultaneously with or shortly after cue onset, the target stimulus was presented. Target detection is affected significantly by the presentation of target-like stimuli appearing before

the cue, labeled as distractors, which ought to be ignored. Importantly, the DIB effect is solely observed if distractors share the target features (Michael et al., 2011; Sahraie et al., 2001; Winther & Niedeggen, 2018) and if multiple distractors and not only one are preceding the target (Winther & Niedeggen, 2017b). Probability of target detection gradually recovers with increasing the cue-target stimulus onset asynchrony (SOA). These characteristics were consistently observed for the target features motion, orientation, and color (Michael et al., 2011; Winther & Niedeggen, 2017a).

The DIB has been related to the activation of a negative attentional set by the repeated presentation of target-like, but task-irrelevant distractors (Niedeggen et al., 2015). The effect demonstrates that conscious access to a relevant target can be prevented if distractors have cumulatively activated a negative attentional set. Comparable distractor effects have been assumed for the Attentional Blink (Zhang et al., 2009, 2011).

ERP studies provided evidence that the DIB relies on a post-perceptual process. Comparing the ERP signatures of detected (hits) and non-detected (misses) targets, no differences were observed regarding early sensory components (Niedeggen et al., 2015; Niedeggen et al., 2004). However, in all studies a late centro-parietal positivity (further labeled as P3b) was significantly more pronounced if the target was detected (Niedeggen et al., 2015; Niedeggen et al., 2004; Niedeggen et al., 2012; Winther & Niedeggen, 2017a). This indicates that the activation of the negative attentional set does not induce suppression on a sensory level of processing, but activates a central gating system preventing the update of target-like information into working memory. These results parallel findings from the attentional blink (Kranczioch et al., 2003; Sergent et al., 2005; Vogel et al., 1998) and support the notion that working memory operations – related to the expression of the P3b – serve as an indicator of conscious access (Dehaene et al., 2011).

In this study, we raise the question whether the reliable DIB effect in the visual modality can be extended to the auditory modality. Although overarching top-down filtering models apply to visual (e.g., (Di Lollo et al., 2005; Moore & Zirnsak, 2017; Olivers & Meeter, 2008)) and auditory stimuli (Sussman et al., 2002), we have to consider that visual and

auditory processing differ in several respects. In comparison with the visual system, the auditory system exhibits a higher temporal integration of incoming information, as well as an extensive preprocessing of sensory input by subcortical structures (VanRullen et al., 2014). Most importantly, perceptual load has an impact on the processing of irrelevant distractors in the visual modality (Lavie, 2010; Lavie & Tsal, 1994), whereas a corresponding effect cannot be consistently observed in the auditory modality (for a review: (Murphy et al., 2017)). Murphy et al. (2013) interpreted the missing influence of perceptual load on auditory distractor detection as a result of additional processing capacity for not attended information exclusive to this modality.

The impact of modality-specific differences has already been demonstrated in studies on the auditory Attentional Blink. Even though several studies suggest an AB-like effect in the auditory modality (Duncan et al., 1997; Horváth & Burgyán, 2011; Shen & Alain, 2010; Shen et al., 2018; Tremblay et al., 2005; Vachon & Tremblay, 2006), it was absent (Potter et al., 1998) or reduced (Arnell & Jenkins, 2004; Soto-Faraco & Spence, 2002) in other studies. If an auditory AB was reported, its time course (T2 detection as a function of the T1/T2 lag) was characterized by a rather linear increase with increasing T1/T2 lag (Shen & Alain, 2010), and the typical lag-1 sparing (Shapiro et al., 1997) was missing (e.g., (Horváth & Burgyán, 2011; Vachon & Tremblay, 2005)). These differences in behavioral effects were also confirmed in ERP studies: Although the reduction of the P3b amplitude observed for the processing of T2 at short T1-T2-SOA is in line with a post-perceptual process (Shen & Alain, 2010; Shen et al., 2018), a reduced N1 wave suggests an effect on sensory processing (Shen & Alain, 2010).

The mixed evidence from research on the auditory AB triggered the question whether the characteristics of the DIB can be observed in the auditory modality. To this end, we designed an auditory set-up containing two streams in which we defined cue, target, and distractor events (see Fig. 1). This set-up allows us to tackle the following experimental questions:

1. Can we identify the behavioral characteristics of a DIB in the auditory domain?



If a *Distractor-induced deafness* (DID) shares the characteristics of a visual DIB, it is expected to depend on the presence of multiple distractors (Winther & Niedeggen, 2017b) and the temporal proximity of cue and target (Sahraie et al., 2001; Winther & Niedeggen, 2017a). Therefore, we hypothesized that an auditory DIB is elicited by multiple, but not by a single distractor. Moreover, we hypothesized that an auditory DIB is more expressed when cue and target are presented simultaneously as compared to a successive presentation.

## 2. Does the DID effect rely on a post-perceptual process?

Following previous ERP-studies on the DIB (Niedeggen et al., 2015; Niedeggen et al., 2004; Niedeggen et al., 2012), we hypothesized that the P3b amplitude is a reliable signature of conscious target detection and that this component is enhanced for detected as compared to non-detected trials. If earlier ERP components are affected by the accessibility of the target – as suggested by Shen & Alain (2010) in an auditory AB study – an effect of distractors on perceptual processing must be considered.

## 2. Method

### 2.1 Participants

The experimental procedure was approved by the local ethics committee at the FU Berlin (027/2019). Raw and aggregated data, stimulus material and the PsychoPsy code are provided in an open repository (<http://dx.doi.org/10.17632/b5qwh2y65d.5>).

Sample sizes were computed a priori using G\*Power (Faul et al., 2007). In both studies, we aimed to detect effects in an F-test with a power of 80% and an  $\alpha$  of .05. For the behavioral study (dependent variable: target detection rate) we 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 24 participants. Similarly, for the ERP study we conservatively assumed a medium sized effect ( $f=.30$ ) for the difference in P3b amplitude (within-subject factor ‘detection’: hits vs. miss), resulting also in a calculated sample size of 24 participants.

For the behavioral study, 27 participants were recruited. The final sample (exclusion criteria: see below) included data of 26 participants (18 women; 18 — 47 years of age;  $M_{age} = 24.36$ ,  $SD = 7.38$ ). Forty-five new participants took part in the ERP experiment. Data of 14 participants were excluded (criteria: see below), leaving a final sample of 31 subjects (22 women; 18—43 years of age;  $M_{age} = 25.94$ ,  $SD = 7.11$ ).

In both experiments, all participants had normal hearing ability (assessed in a pretest), normal or corrected-to-normal vision, and reported no history of neurological or psychiatric disorders. They were recruited in the university environment, gave their written informed consent and received course credit for their participation.

The following exclusion criteria were defined: (1) unreliable target detection during pretest (correct target detection in less than 60% of trials), indicating hearing problems or insufficient understanding of the task, (2) overall poor psychophysiological performance (less than 25% correct target detection in the 0-distractor condition), (3) unreliable ERP average due to a high number of EOG/EEG artefacts (eye blinks/movements, movement artefacts, or high EEG alpha activity ( $>80 \mu V$ )), resulting in less than 10 valid trials per hit/miss condition, (4) ceiling effects in the multiple distractor condition (less than 10% miss trials) in the ERP study, leading to less than 10 valid trials in the miss condition. Similar exclusion criteria (criterion 2-4) have been applied during previous DIB studies (Niedeggen et al., 2015; Winther & Niedeggen, 2017a).

These criteria lead to the exclusion of one participant in the behavioral study (criterion 1), and to the exclusion of 14 participants in the ERP study. In the ERP study, two participants had to be excluded because of technical problems or not completing the experiment. Additionally, one participant was excluded due to criterion 1, three participants showed poor psychophysiological performance (criterion 2), two participants produced too many artifacts (criterion 3) and another six produced less than 10% misses (criterion 4).

## **2.2 Stimuli, procedure and design**

In both studies, the rapid serial auditory presentation (RSAP) sequences were presented using a Python protocol (version 3.6.8) on a Windows-running PC. No part of the

study procedures were pre-registered prior to the research being conducted. The trials were constructed as follows:

Two auditory streams were presented simultaneously through headphones (Sennheiser OCX 686i, Wedemark-Wennebostel, Germany). The auditory stimuli were created and edited using the programs “Tone Generator” and “WavePad Editor” (NCH Software, Greenwood, USA). One RSAP sequence consisted of pure sine-wave tones (behavioral study: 40 tones resulting in a stream length of 4,000 ms, ERP study: 50 tones resulting in a stream length of 5,000 ms). Each tone was randomly selected from a set of seven sine wave tones in the frequency range of 1,800 – 2,200 Hz and was presented for 30 ms with an inter-stimulus interval of 70 ms. In this tone sequence, a deviant (overlay of two 30 ms tones defined by 1,600 and 2,400 Hz) was embedded, which served as cue (see Figure 1). The second, simultaneously presented RSAP sequence was defined by a continuous tone, which was modulated at 5 Hz in a frequency range from 270 – 330 Hz. The amplitude of the continuous tone was reduced (-20 dB) in contrast to the first RSAP sequence. The target event was defined by an increase in amplitude (+10 dB) for 100 ms. The participant’s task was to decide whether the target was presented simultaneously – or following – the onset of the cue. The responses had to be provided following the offset of the RSAP sequence. The delayed responses (first cue: yes/no, second target: yes/no) also allowed a temporal separation between the sensory processing of the relevant events, and the motor preparation and response.

Increases in the amplitude of the continuous tone preceding the cue were defined as *distractors* and ought to be ignored. Distractors were positioned randomly within the pre-cue epoch. To avoid confusion on the categorization of distractor and target events, a sufficient temporal separation of both events was provided: The last distractor in the RSAP stream occurred at least 500 ms before cue onset. Distractors were exclusively presented in the pre-cue epoch.

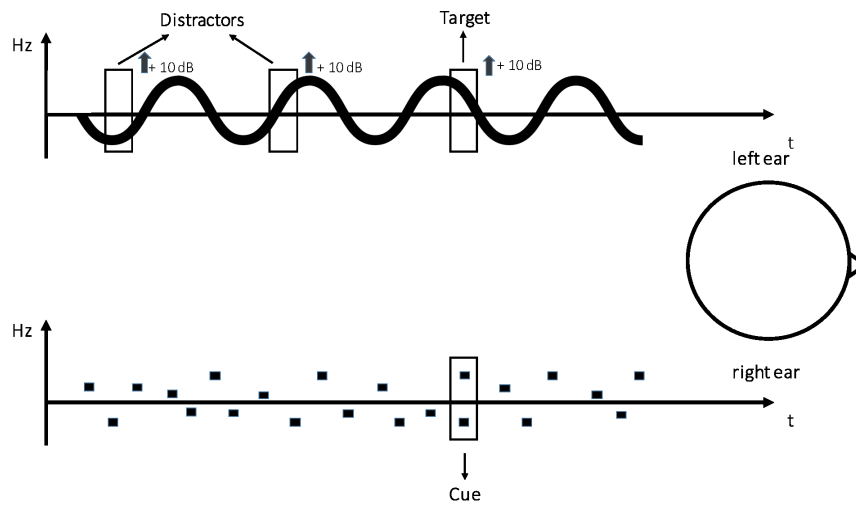
A training phase (32 trials), which included verbal feedback, served to ensure a reliable categorization of the events cue, target, and distractor. The training phase preceding

both experiments included the same trial format and response options used during the main experiments. During the presentation of the audio sequence, a red fixation cross (1.02° in diameter) was presented on the screen, at which participants were instructed to fixate their gaze. At the end of each trial, subjects were asked whether a cue was present (question 1: “Did you hear a deviant tone?”) and whether or not a target was detected in the preceding trial (question 2: “Did you hear a change in the continuous tone simultaneous to (or after) the deviant tone?”). Both questions appeared consecutively on the computer screen and responses were given by pressing a corresponding button on the keyboard. Response time was not limited. Participants were instructed to respond as accurately as possible. Bimodal verbal report was chosen as dependent measure in analogy to visual DIB studies (Niedeggen et al., 2015; Niedeggen et al., 2012). Figure 1 illustrates the design of a trial.

The behavioral study tested the prerequisites of an auditory DID effect. The experiment comprised 252 trials (duration: 4,000 ms per trial). As within-participant factors, we manipulated the cue-target SOA (0 ms vs. 300 ms) and the number of distractors presented in the pre-cue epoch (0 vs. 1 vs. 6-8). The 300 ms SOA-condition was implemented to gain information about the time course of the effect. The SOA conditions consisted of 84 trials each. In each SOA condition, we presented 21 trials without distractors, 21 trials with one distractor and 42 trials with multiple distractors. In total, 168 trials including a cue and target were presented. The remaining 84 trials served as control conditions (21 trials without cue and target and without distractors, 21 trials without cue and target but multiple distractors, 21 trials with cue, no target and no distractors, and 21 trials with cue, no target and multiple distractors). Including the between-factor ‘presentation mode’, we controlled for an effect of auditory segregation. In one group of participants (n=14), the auditory streams were separately presented to the right (cue sequence) and the left (target sequence) ear. In a second group (n=12), both auditory streams were superimposed and the cue and target sequence were therefore presented to the left and to the right ear.

## Figure 1

## Experimental design



*Note.* Schematic diagram of two RSAP streams used in the ERP study and the separate streams group in the behavioral study. Two auditory streams were presented simultaneously during each trial. In the right ear, a sequence of pure tones (1,800 - 2,200 Hz) was presented, while in the left ear the participants heard a continuous tone (270 - 330 Hz). A short increase (100 ms) in amplitude in the continuous tone was defined as target, but only if it was accompanied by a deviant tone (cue) on the other ear (SOA = 0 ms). During the behavioral study, the target could also be presented after the cue (SOA = 300 ms). Increases in amplitude preceding the cue were called distractors.

The ERP experiment took place in a sound-attenuated chamber with dimmed indirect lightning. Importantly, here all participants heard two separate auditory streams (see Fig. 1). Participants sat in front of a 20" monitor (Sony Trinitron Multiscan G520, Tokyo, Japan) at a viewing distance of 57 cm with the head stabilized on a chin rest.

240 trials were presented with a duration of 5,000 ms each. The cue was presented at a random temporal position within the time window of 3,100 to 4,000 ms after trial onset. 150 trials contained cue and target with cue-target SOA kept constant at 0 ms. Within this condition, the experimental within-factor 'distractor' was defined: Multiple distractor episodes (6-8) were presented in 90 trials, a single distractor episode was presented in 30 trials, and in 30 trials, no distractor preceded cue and target. The remaining trials (90) served as control: In 45 trials, solely the cue but no target was presented (cue-only conditions: 15 trials without distractors, 15 trials with 1 distractor, and 15 trials with multiple distractors). These trials allowed for the assessment of false alarms (i.e., falsely reported target after correctly

detected cue). In another 45 trials, neither cue nor target were presented (15 trials without distractors, 15 trials with 1 distractor, and 15 trials with multiple distractors).

## 2.3 EEG recording

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, with impedance kept below 10 k $\Omega$ . The ground electrode was positioned at FCz. To control for horizontal and vertical eye movements, four additional electrodes were positioned at the outer canthi (horizontal electrooculogram) and at the sub- and supraorbital ridges of the right eye (vertical electrooculogram). The EEG signal was recorded at a 500 Hz sampling rate using a 40-channel NuAmps amplifier (Software Acquire, Neuroscan Labs, Neurosoft Inc., El Paso, TX, USA) and was band-pass filtered online (0.1 - 200 Hz). The acquired data were analyzed using the software "BrainVision Analyzer" (Version 2.1, Brain Products GmbH, Gilching, Germany).

In each trial, two markers were defined: The first one referred to the onset of the last distractor event and the second to the onset of the cue. Based on these markers, EEG data were segmented offline into epochs of 900 ms (-100 to 800 ms epoch length), filtered (0.3 – 30 Hz, 50 Hz Notch filter) and baseline corrected (-100 to 0 ms). Running a semi-automatic artefact rejection, trials which contained artefacts (ocular or muscular), slow drifts due to movements, or high EEG alpha activity (>80  $\mu$ V) were identified and excluded from further analysis. If an average in an experimental condition comprised less than 10 valid trials, the data set of the participant was excluded from analysis.

## 2.4 Statistical analysis

### 2.4.1 Behavioral data

Data analysis procedures were not pre-registered prior to conducting the research. For each participant, target detection rate (i.e., correct detection of the target event if the cue was also correctly identified) was computed for each experimental condition.

In the behavioral study, data acquired were analyzed in a 2 x 3 x 2 analysis of variance (ANOVA), including the within-subject factors SOA (0 ms vs. 300 ms) and number of distractors (0 vs. 1 vs. 6-8) and the between-subject factor presentation mode (separate vs. superimposed streams). In case of a significant interaction, post-hoc comparisons were computed. Greenhouse-Geisser corrected F-values will be reported.

Behavioral data in the ERP study were analyzed in a one-way repeated measure ANOVA with the within-subject factor number of distractors (0 vs. 1 vs. 6-8), followed by pairwise comparisons in case of a significant main effect.

#### 2.4.2 ERP data

The analysis of ERPs focused on trials in which cue-target presentation was preceded by multiple distractors. For this experimental condition, data were averaged separately for each electrode position according to the participant's response ("hit" or "miss"). Additionally, ERPs were averaged for the event "cue only", which allowed estimating the ERP responses to the deviant tone (cue), and for the event "final distractor". The latter analysis served to assess ERP responses to an irrelevant increase in loudness and is provided in Supplement 1.

In a first step, the time course of the global activity and its relation to the spatial distribution of the electrical activity driven by the processing of the cue-target-compound was analyzed. The global activity was defined by the global field power (GFP) based on grand-averaged ERP data for the condition "cue and target, multiple distractors". As shown in Figure 2a, a first peak was identified at 240 ms, followed by a second, more sustained period of stable activity between 450 and 600 ms. Inspection of the reference-independent topographical distribution (Fig. 2b and c) showed that the first peak was related to a frontal negativity, and the second to a centro-parietal positivity (further labeled as P3b). Based on this visual inspection, we then tested for significant shifts of activation in the caudal dimension (anterior vs. posterior). To this end, the time course of the reference-independent activation of each electrode was split in ten consecutive 60-ms bins covering the time range 0 to 600 ms after cue/target onset. Since the topographical maps revealed activation peaks

at anterior and posterior sites, electrodes were clustered based on their caudal position (anterior: AFz, F3, Fz, F4, FC1, FC2; posterior: Cz, P3, Pz, P4, O1, O2). A first repeated measures ANOVA containing the factors 'time' (10 time windows) and 'caudality' (anterior vs. posterior) confirmed a significant shift of activation in the caudal dimension ( $F(9, 270) = 13.997, p < .001, \eta_p^2 = .318$ ). This result justified comparing two consecutive time windows, respectively, using repeated measures ANOVAs including the factors 'time' and 'caudality'. The results of this analysis are illustrated in Figure 2.

In a second step, the experimental effects were analyzed accordingly. Reference-dependent mean amplitudes in the above defined 60-ms bins were computed separately for the conditions "cue only", "cue-target: miss" and "cue-target: hit". First, a repeated measures ANOVA containing the factors 'time' (10 time windows), 'caudality' (anterior vs. posterior) and 'condition' (cue only vs. miss vs. hit) confirmed significant differences between the conditions as a factor of time (interaction time x condition:  $F(7.43, 223.09) = 2.552, p = .013, \eta_p^2 = .078$ ; interaction time x cluster x condition:  $F(8.03, 240.99) = 2.305, p = .021, \eta_p^2 = .071$ ). Therefore, post-hoc comparisons between the three relevant conditions could be conducted. Consecutively, or each of the ten time windows, three statistical comparisons were performed running repeated measures ANOVAs: (1) Hit vs. Cue only, (2) Miss vs. Cue only, and (3) Hit vs. Miss. The results of these comparisons are shown in Table 2 and illustrated in Figure 3. In order to consider spatial shifts in the expression of experimental effects, each ANOVA contained the factor 'caudality'.

In a third step, we tested the reliability of the experimental effects obtained for the crucial comparison "hit vs. miss" running a randomization test. This procedure was chosen to provide insight into whether the effects could also be detected in randomly selected subsamples. The size of the subsamples ( $N=24$ ) was based on the results of the a priori calculated sample size (see section 2.1).

In each run, 24 out of the 31 ERP data sets were randomly selected. For each selected subsample, paired t-statistics (hit vs. miss) were computed (i.e., "correct pairings").



Pairings within the subsample were then randomized by switching the assignment (hit vs. miss) in 12 of the 24 pairs, while the correct assignment was kept for the remaining 12 pairs. For these “random pairings”, corresponding t-statistics were computed (“random hit” vs. “random miss”). This randomization procedure was repeated 100 times. The random pairs served to create a matching sample for the correct pairs. If differences between hits and misses identified in the second step of analysis depict reliable effects, substantially larger t-values will be observable for correct pairings in contrast to random pairings. Results of the ERP analysis reported in the following section are supported by the outcome of this randomization test. The resulting data are available in Supplement 2 and will be briefly reported at the end of the result section.

### 3. Results

#### 3.1 Behavioral Study

Mean detection rates are presented in Table 1.

Data analysis revealed that target detection was significantly affected by the number of distractors preceding the target (Factor ‘number of distractors’:  $F(1.471, 35.312) = 12.99, p < .001, \eta_p^2 = .351$ ). To decide whether this main effect was driven by the multiple distractor condition, we performed pairwise post-hoc comparisons between the three conditions. Targets were less likely to be detected, if multiple distractors were presented (0 vs. 1 distractor:  $F(1, 25) = 1.49, p = .233, \eta_p^2 = .056$ ; 0 vs. multiple distractors:  $F(1, 25) = 15.65, p = .001, \eta_p^2 = .385$ ; 1 vs. multiple distractors:  $F(1, 25) = 15.33, p = .001, \eta_p^2 = .380$ ).

The factor SOA did not yield significance,  $F(1, 24) = 3.71, p = .066, \eta_p^2 = .134$ . However, the effect of number of distractors was differently expressed for the SOA conditions (interaction ‘number of distractors’ x ‘SOA’:  $F(2, 48) = 6.47, p = .003, \eta_p^2 = .212$ ). The post-hoc comparisons confirmed that the effect of multiple distractors was only expressed for the short SOA (SOA 0 ms:  $F(2, 50) = 6.47, p < .001, \eta_p^2 = .378$ ; SOA 300 ms:  $F(1.479, 36.974) = 2.99, p = .076, \eta_p^2 = .107$ ).

The interaction of the factors ‘SOA’ x ‘number of distractors’ was additionally modulated by the between-subject factor ‘presentation mode’,  $F(2, 48) = 3.49, p = .039, \eta_p^2 = .13$ . This effect was driven by lower detection rates in the superimposed-streams condition as compared to the separate-streams condition if no distractors were presented. Importantly, the difference between target detection after 1 and multiple distractors was not modulated by presentation mode, neither at short SOA,  $F(1, 24) = .13, p = .719, \eta_p^2 = .005$ , nor at long SOA,  $F(1, 24) = 1.37, p = .202, \eta_p^2 = .054$ , showing the presence of a distractor effect in both presentation modes.

The analysis of the control conditions without a target revealed that mean false alarm rates were 4.77% ( $SD = 11.12$ ) without distractors and 17.42% ( $SD = 19.37$ ) with distractors. False alarm rates were significantly higher if multiple distractors preceded the cue,  $F(1, 25) = 9.99, p = .004, \eta_p^2 = .286$ .

**Table 1**

*Target detection rates in behavioral and ERP study*

	Behavioral study				ERP study
	Separate Streams		Superimposed Streams		Separate Streams
Distractors	SOA 0 ms	SOA 300 ms	SOA 0 ms	SOA 300 ms	SOA 0 ms
0	$M=96.51$ CI [88.67, 104.16]	$M=95.15$ CI [87.78, 102.52]	$M=82.13$ CI [73.87, 90.38]	$M=85.83$ CI [77.86, 93.79]	$M=72.45$ CI [64.43, 80.48]
1	$M=87.21$ CI [78.32, 96.09]	$M=94.68$ CI [86.04, 103.31]	$M=88.24$ CI [78.65, 97.84]	$M=82.17$ CI [72.84, 91.49]	$M=76.15$ CI [68.49, 83.82]
6-8	$M=73.06$ CI [60.79, 85.32]	$M=86.89$ CI [74.81, 98.98]	$M=71.75$ CI [58.51, 84.99]	$M=71.73$ CI [68.68, 94.78]	$M=64.49$ CI [57.17, 71.80]

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

**3.2 ERP study**

**3.2.1 Behavioral data**

The behavioral data acquired in the ERP study replicated the pattern of results obtained in the behavioral study for the short SOA-condition. The within-subject factor

'number of distractors' (0 vs. 1 vs. 6-8 distractors) had a significant effect on target detection,  $F(2, 60) = 7.14, p = .002, \eta_p^2 = .192$ . Pairwise post-hoc comparisons indicated that this effect was solely due to a reduced hit rate in the multiple distractor condition (0 vs. 1 distractor:  $F(1, 30) = 1.30, p = .263, \eta_p^2 = .042$ ; 0 vs. multiple distractors:  $F(1, 30) = 7.27, p = .011, \eta_p^2 = .195$ ; 1 vs. multiple distractors:  $F(1, 30) = 12.78, p = .001, \eta_p^2 = .299$ ).

Participants produced more false alarms in the presence of multiple distractors ( $M = 34.00\%$ ,  $SD = 26.26$ ) than if no distractors were preceding the target ( $M = 16.79\%$ ,  $SD = 18.33$ ),  $F(1, 30) = 14.47, p = .001, \eta_p^2 = .325$ .

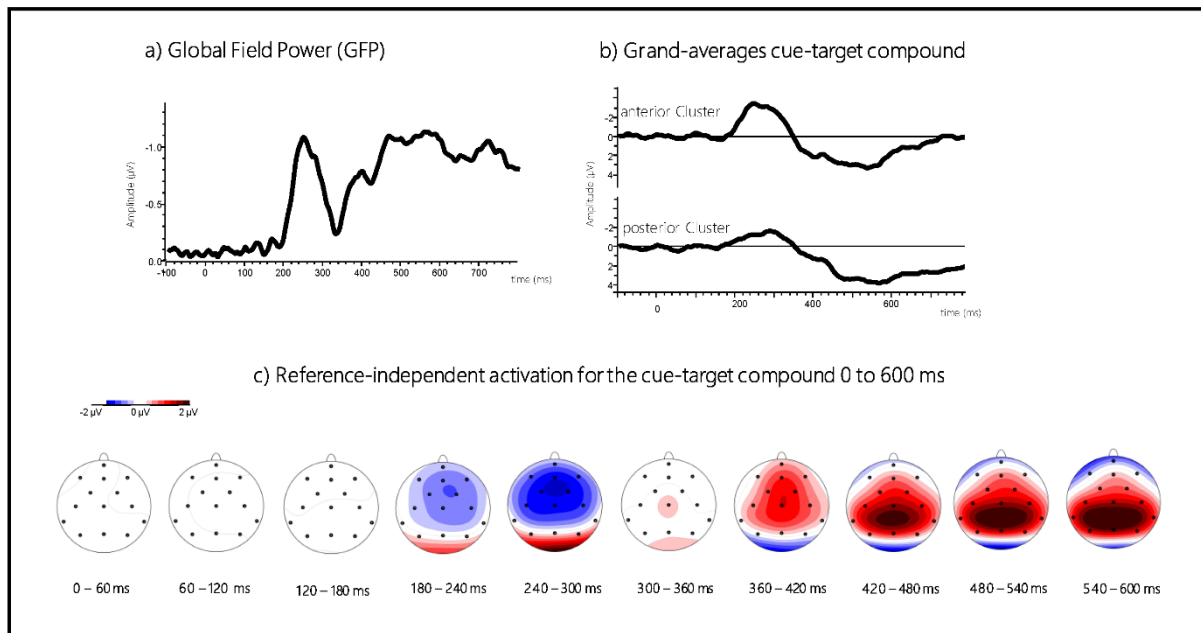
### 3.2.2 ERP data

Grand-averaged data observed at the anterior and posterior electrode cluster for the cue-target compound and the "cue only" condition are presented in Table 3 and are illustrated in Figure 3. The maps are based on the reference-free activation and cover a temporal range from 0 to 600 ms. (see Fig. 2)

An initial ANOVA confirmed shifts in the factor 'caudality' (anterior vs. posterior) of the activation within the 600 ms time range,  $F(2, 270) = 13.997, p < .001, \eta_p^2 = .318$ . Data were then divided into ten 60-ms time bins and the subsequent time windows were tested for a significant interaction with the factor 'caudality' (for descriptive values see Supplement 3). In line with the visual inspection, these ANOVAs confirmed an increase in frontal negativity at 180 ms (120 – 180 ms vs. 180 - 240 ms:  $F(1, 30) = 26.93, p < .001, \eta_p^2 = .473$ ). The negativity becomes more widespread in the following time window (180 – 240 ms vs. 240 – 300 ms:  $F(1, 30) = 14.33, p < .001, \eta_p^2 = .323$ ). Starting at 360 ms, a posterior positivity becomes prominent (300 – 360 ms vs. 360 – 420 ms:  $F(1, 30) = 32.57, p < .001, \eta_p^2 = .520$ ) which remains stable from 360 to 540 ms. In the following, we refer to this broad time range as P3b.

## Figure 2

## Global Field Power and spatial distribution of electrical brain activity



*Note.* Time course and spatial distribution of electrical brain activity driven by the cue-target compound in the multiple distractor condition. (a) The Global Field Power (GFP) revealed two maxima in activation: a first peak around 240 ms and a second, long-lasting activity from 450 ms onwards (b). According to the grand-averaged ERP data, the first peak is based on a frontal negativity and the sustained activation reflects a widespread positivity with a more posterior maximum. (c) Reference-independent plots of cortical activity confirm the impression of the grand-averaged ERPs.

After a repeated measures ANOVA containing the factors 'time' (10 time windows), 'caudality' (anterior vs. posterior) and 'condition' (cue only vs. miss vs. hit) had confirmed significant differences between the conditions as a factor of time (interaction time x condition:  $F(7.43, 223.09) = 2.552, p = .013, \eta_p^2 = .078$ ; interaction time x cluster x condition:  $F(8.03, 240.99) = 2.305, p = .021, \eta_p^2 = .071$ ), post-hoc comparisons between the conditions were computed for each time window. The analysis of ERP data was focused on three comparisons: First, detected cue-target compounds (hits) were compared with the cue only condition. This analysis reveals the ERP signature of a hit when contrasted to a baseline condition without target. Second, misses were compared to the cue only condition. This analysis shows whether the processing of a missed target is comparable with the processing of a cue. Finally, hits were compared directly to misses to identify ERP effects associated

with conscious access to a target stimulus. Note that for all analyses, only trials with multiple distractors were included.

The statistical analysis was performed for the ten consecutive time bins, and included the spatial factor 'caudality'. The results are depicted in Table 2.

*ERP signatures of a detected target:* The grand-averaged ERPs associated with the detection of a cue in the cue only condition and the detection of the cue-target compound are presented in Figure 3a. Descriptive values are shown in Table 3, and the results of the statistical analysis are displayed in Table 2. In the early part of the frontal negativity (180 – 240 ms), amplitude was significantly enhanced for hits. Post-hoc comparisons confirmed that the enhancement for detected targets was selectively expressed in the anterior cluster,  $F(1, 30) = 5.12$ ,  $p = .031$ ,  $\eta_p^2 = .147$ , but not in the posterior cluster,  $F(1, 30) = .41$ ,  $p = .527$ ,  $\eta_p^2 = .013$ . The effect was even more pronounced in the late part of the frontal negativity (240 – 300 ms). Again, the enhancement was found at anterior,  $F(1, 30) = 11.26$ ,  $p < .001$ ,  $\eta_p^2 = .237$ , but not at posterior leads,  $F(1, 30) = .15$ ,  $p = .903$ ,  $\eta_p^2 = .000$ . As depicted in Figure 3a, the topography of the frontal effect remained stable in the two consecutive windows of analysis.

In three successive temporal bins (360 – 540 ms), referring to the P3b range, a hit was consistently associated with a significant increase in positive amplitude. Although the topographical distribution (see Fig. 3a) indicated a shift to parietal leads, the statistical analysis did not reveal a significant modulation by the factor 'caudality' (see Table 2).

*ERP Signatures of an undetected target:* The grand-averaged ERPs associated with the detection of a cue in the cue only condition and the miss of a target are presented in Figure 3b. Descriptive values are presented in Table 3, and the results of the statistical analysis are depicted in Table 2.

Table 2

Summary of the statistical analysis for ERPs between 0 and 600 ms after cue/target onset

	0 - 60 ms	60 - 120 ms	120 - 180 ms	180 - 240 ms	240 - 300 ms	300 - 360 ms	360 - 420 ms	420 - 480 ms	480 - 540 ms	540 - 600 ms
	$F(1,30) = 3.312$	$F(1,30) = .045$	$F(1,30) = 3.901$	$F(1,30) = 1.279$	$F(1,30) = 2.922$	$F(1,30) = 4.021$	$F(1,30) = 12.488$	$F(1,30) = 11.721$	$F(1,30) = 12.000$	$F(1,30) = 3.673$
Condit	$p = .079$	$p = .833$	$p = .058$	$p = .267$	$p = .098$	$p = .054$	$p = .001$	$p = .002$	$p = .002$	$p = .065$
Cluster	$\eta = .099$	$\eta = .002$	$\eta = .115$	$\eta = .041$	$\eta = .089$	$\eta = .118$	$\eta = .294$	$\eta = .606$	$\eta = .286$	$\eta = .109$
HIT vs. CUE	$F(1,30) = .000$	$F(1,30) = .058$	$F(1,30) = .312$	$F(1,30) = 5.974$	$F(1,30) = 15.239$	$F(1,30) = .026$	$F(1,30) = 1.743$	$F(1,30) = .315$	$F(1,30) = .027$	$F(1,30) = .543$
Condit	$p = .986$	$p = .812$	$p = .580$	$p = .021$	$p < .001$	$p = .872$	$p = .197$	$p = .579$	$p = .871$	$p = .470$
Cluster	$\eta = .000$	$\eta = .002$	$\eta = .010$	$\eta = .166$	$\eta = .337$	$\eta = .001$	$\eta = .055$	$\eta = .010$	$\eta = .001$	$\eta = .018$
HIT vs. MISS	$F(1,30) = 1.222$	$F(1,30) = .164$	$F(1,30) = 3.259$	$F(1,30) = .014$	$F(1,30) = 1.192$	$F(1,30) = 1.518$	$F(1,30) = 3.184$	$F(1,30) = .763$	$F(1,30) = .167$	$F(1,30) = 4.445$
Condit	$p = .278$	$p = .689$	$p = .081$	$p = .906$	$p = .284$	$p = .227$	$p = .084$	$p = .389$	$p = .686$	$p = .043$
Cluster	$\eta = .039$	$\eta = .005$	$\eta = .098$	$\eta = .000$	$\eta = .038$	$\eta = .048$	$\eta = .096$	$\eta = .025$	$\eta = .006$	$\eta = .129$
HIT vs. CUE	$F(1,30) = .097$	$F(1,30) = .351$	$F(1,30) = 2.123$	$F(1,30) = .323$	$F(1,30) = 3.511$	$F(1,30) = .356$	$F(1,30) = 2.55$	$F(1,30) = .123$	$F(1,30) = .595$	$F(1,30) = .483$
Condit	$p = .758$	$p = .558$	$p = .155$	$p = .574$	$p = .071$	$p = .555$	$p = .618$	$p = .728$	$p = .447$	$p = .493$
Cluster	$\eta = .003$	$\eta = .012$	$\eta = .066$	$\eta = .011$	$\eta = .105$	$\eta = .012$	$\eta = .008$	$\eta = .004$	$\eta = .019$	$\eta = .016$
HIT vs. MISS	$F(1,30) = .536$	$F(1,30) = .048$	$F(1,30) = .000$	$F(1,30) = 2.302$	$F(1,30) = .353$	$F(1,30) = .244$	$F(1,30) = 2.298$	$F(1,30) = 2.958$	$F(1,30) = 5.116$	$F(1,30) = .098$
Condit	$p = .470$	$p = .828$	$p = .994$	$p = .140$	$p = .557$	$p = .625$	$p = .140$	$p = .096$	$p = .031$	$p = .756$
Cluster	$\eta = .018$	$\eta = .002$	$\eta = .000$	$\eta = .071$	$\eta = .012$	$\eta = .008$	$\eta = .071$	$\eta = .090$	$\eta = .146$	$\eta = .003$
HIT vs. MISS	$F(1,30) = .083$	$F(1,30) = .070$	$F(1,30) = .797$	$F(1,30) = 7.053$	$F(1,30) = .730$	$F(1,30) = .986$	$F(1,30) = .637$	$F(1,30) = .065$	$F(1,30) = .223$	$F(1,30) = 1.465$
Condit	$p = .775$	$p = .793$	$p = .379$	$p = .013$	$p = .400$	$p = .329$	$p = .431$	$p = .800$	$p = .641$	$p = .236$
Cluster	$\eta = .003$	$\eta = .002$	$\eta = .026$	$\eta = .190$	$\eta = .024$	$\eta = .032$	$\eta = .021$	$\eta = .002$	$\eta = .007$	$\eta = .047$

Note. Summary of the results of the statistical analysis of the comparisons “Hit vs. Cue only”, “Miss vs. Cue only”, and “Hit vs. Miss”. Each analysis also comprised the factor ‘caudality’ referring to the electrode cluster. Significant results for the main effect of ‘condition’ or the interaction of ‘condition’ and ‘caudality’ are highlighted in bold.

Table 3

Descriptive values for ERP amplitudes

Electrode Cluster	0 - 60 ms	60 - 120 ms	120 - 180 ms	180 - 240 ms	240 - 300 ms	300 - 360 ms	360 - 420 ms	420 - 480 ms	480 - 540 ms	540 - 600 ms	
CUE	anterior	M = -.223 95% CI [-.62, .17]	M = -.032 95% CI [-.50, .44]	M = -.289 95% CI [-.85, .27]	M = -1.278 95% CI [-1.84, -.72]	M = -2.287 95% CI [-2.99, -1.58]	M = -1.474 95% CI [-2.28, -.67]	M = 1.009 95% CI [1.19, 1.82]	M = 1.940 95% CI [1.06, 2.82]	M = 2.565 95% CI [1.74, 3.39]	M = 2.404 95% CI [1.59, 3.21]
	posterior	M = -.186 95% CI [-.43, .06]	M = -.128 95% CI [-.49, .24]	M = -.284 95% CI [-.64, .07]	M = -1.095 95% CI [-1.51, -.67]	M = -1.509 95% CI [-2.04, -.98]	M = -1.227 95% CI [-1.65, -.80]	M = .320 95% CI [-.22, .86]	M = 1.624 95% CI [1.08, 2.17]	M = 2.432 95% CI [1.88, 2.98]	M = 2.577 95% CI [1.98, 3.18]
MISS	anterior	M = -.026 95% CI [-.58, .53]	M = .163 95% CI [-.47, .79]	M = .331 95% CI [-.13, .79]	M = -1.340 95% CI [-1.88, -.80]	M = -2.974 95% CI [-3.78, -2.17]	M = -1.130 95% CI [-2.08, -.19]	M = 1.732 95% CI [.865, 2.59]	M = 2.347 95% CI [1.32, 3.37]	M = 2.841 95% CI [1.91, 3.77]	M = 3.070 95% CI [2.14, 4.00]
	posterior	M = -.099 95% CI [-.26, .46]	M = -.116 95% CI [-.53, .30]	M = -.057 95% CI [-.49, .38]	M = -.970 95% CI [-1.35, -.59]	M = -1.518 95% CI [-2.09, -.95]	M = -.636 95% CI [-1.23, -.04]	M = .870 95% CI [.29, 1.44]	M = 1.902 95% CI [1.05, 2.75]	M = 2.445 95% CI [1.76, 3.13]	M = 2.995 95% CI [2.32, 3.67]
HIT	anterior	M = .212 95% CI [1.14, .56]	M = .057 95% CI [-.45, .57]	M = .218 95% CI [-.21, .65]	M = -2.058 95% CI [-2.57, -1.54]	M = -3.254 95% CI [-3.85, -2.66]	M = -.820 95% CI [-1.48, -.16]	M = 2.356 95% CI [1.67, 3.04]	M = 3.091 95% CI [2.11, 4.07]	M = 3.546 95% CI [2.72, 4.38]	M = 2.918 95% CI [2.08, 3.76]
	posterior	M = .253 95% CI [-.43, .06]	M = -.129 95% CI [-.56, .31]	M = .052 95% CI [-.30, .40]	M = -.898 95% CI [-1.32, -.48]	M = -1.546 95% CI [-2.04, -.98]	M = -.621 95% CI [-1.04, -.21]	M = 1.122 95% CI [.54, 1.70]	M = 2.527 95% CI [1.94, 3.12]	M = 3.35 95% CI [2.69, 4.02]	M = 3.359 95% CI [2.55, 4.17]

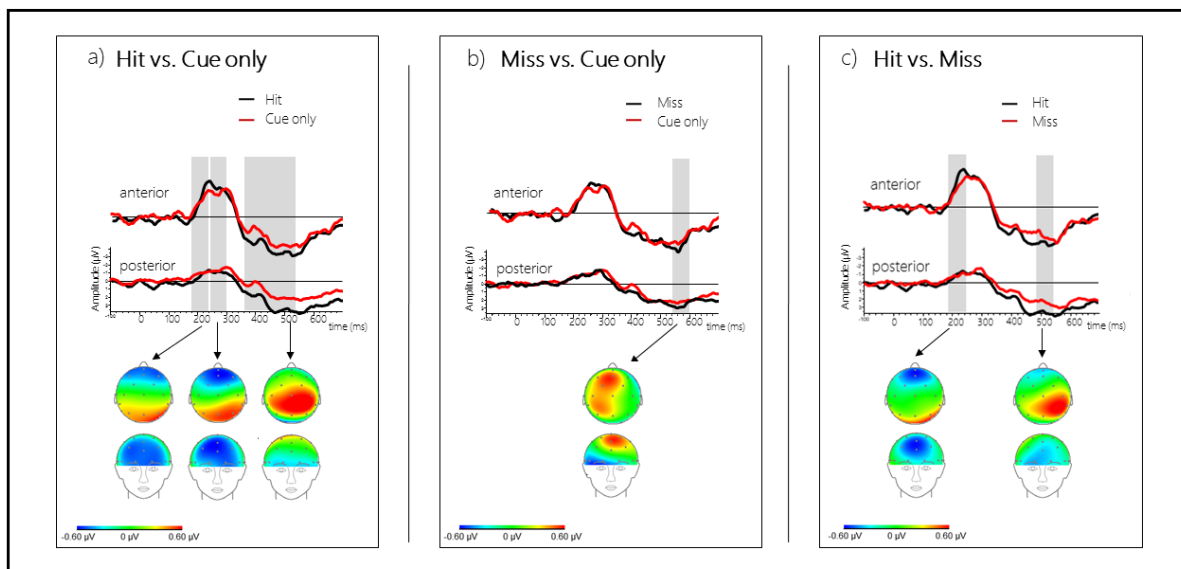
Note. Mean amplitudes (in  $\mu\text{V}$ ) and 95% confidence intervals (CIs) of ERPs observed in the conditions “Cue only”, “Miss” and “Hit”. Descriptive values are presented separately for each of the ten time windows and for the factor ‘caudality’ (anterior vs. posterior electrode cluster).

Visual inspection of grand-averaged data indicated a small enhancement of the frontal negativity for misses (Fig. 3b). However, the statistical analysis (see Table 2) showed that cue only and misses did not differ in the early (180 – 240 ms), or the late part (240 – 300 ms) of the negativity.

In the late time ranges referring to the P3b, a difference was exclusively expressed in the latest time window (540 – 600 ms). In this last time bin, ERPs referring to the miss condition were significantly more positive going than for cue only. This effect was not more pronounced at the posterior cluster.

### Figure 3

*ERPs elicited by hits, misses and cue only*



*Note.* Grand-averaged ERP waveforms elicited by the cue-target compound or cue only, respectively. Responses to the cue-target compound were separated into hits (i.e., correctly detected targets after a detected cue) and misses (i.e., undetected targets after a detected cue) according to the participant's assessment. Only trials with multiple distractors preceding the cue were included in the analysis. Reference-independent topographic distributions for the time windows in which analysis revealed significant differences between the respective conditions are presented below the grand-averages. (A) Comparison between trials, during which the cue was presented alone (red line) in comparison to trials, in which the cue-target compound was detected (black line), presented for the anterior and posterior electrode cluster defined above. The response to hits was accompanied by a long lasting, prominent frontal negativity (180 – 300 ms) and a more pronounced late positivity with a centro-parietal maximum (P3) between 360 and 540 ms. (B) ERP responses to misses (black line) in comparison to cue only (red line) showed a larger, very late positive wave with central maximum (540 – 600 ms), but did not differ regarding earlier frontal processes. (C) Hits (black line) elicited a larger early frontal negativity (180 – 240 ms) and a larger centro-parietal P3 (480 – 540 ms) than misses (red line).



*ERP signatures of detected vs. missed targets:* The grand-averaged ERPs associated with successful and failed detection of the cue-target compound after multiple distractors are shown in Figure 3c. Descriptive values are presented in Table 3 and the results of the ANOVAs are displayed in Table 2.

Statistical significant differences between hits and misses were observed in two time windows: First, in the range of the early frontal negativity (180 - 240 ms), amplitude was enhanced in case of a hit. The interaction with the factor 'caudality' indicated that the differences were more pronounced at the anterior cluster,  $F(1, 30) = 7.053$ ,  $p = .013$ ,  $\eta_p^2 = .190$ . This difference between hits and misses was only observed for the early part of the negativity, and did not extend to the following time window. The second difference was obtained within the P3b range (480 – 540 ms). In line with the visual inspection (see Figure 3c), the positivity was more expressed for hits. Although the effect was apparently more pronounced at posterior electrodes, no interaction with the factor 'caudality' was observed.

To test the reliability of the two observed differences between hits and misses, a randomization test was computed consecutively. In 100 runs, we determined the probability to replicate the results in smaller subsamples (N=24 each). For both time windows chosen for analysis (180 – 240 ms and 480 - 540 ms), a similar pattern was revealed for the (repeated) analysis of subsamples, indicating that correct pairings could be separated clearly from random pairings.

The randomization test confirmed that hit and miss condition can be separated reliably in the time window of the early negativity. If the experimental condition was correctly assigned in the randomly selected subsamples, the mean t-value ( $M = -2.001$ ,  $SD = .402$ ) was substantially larger than in the subsamples with a random assignment of conditions ( $M = .025$ ,  $SD = .924$ ). Moreover, the critical t-value (1.71) was exceeded in 79 out of 100 comparisons for correct pairings (random pairings: 3 times out of 100). The same pattern held for the effect in the P3 range: In case of a correct assignment of hit and miss condition, t-values ( $M = 2.025$ ,  $SD = .467$ ) were larger than t-values based on random assignment ( $M = .046$ ,  $SD = 1.037$ ). For correct pairings, the critical t-value (1.71) was also exceeded in 79 out

of 100 comparisons (random pairings: 4 times out of 100). The results are depicted in Supplement 2.

## 4. Discussion

### 4.1 Summary of results

The current study aimed to test whether the prerequisites of distractor-induced blindness identified in the visual modality also apply to the auditory modality. Moreover, we examined whether an ERP signature comparable to the one observed for visual stimuli likewise characterizes explicit auditory target detection. The behavioral data confirmed that a distractor-induced deafness (DID) can be elicited, if multiple task-irrelevant distractors that share the target's features precede the presentation of cue and target. In line with previous research on distractor-induced blindness (Michael et al., 2012; Milders et al., 2004), the inhibitory effect is more pronounced if cue and target are presented simultaneously. Comparing the ERP effects associated with failed and successful target detection, we confirmed that conscious access to the target is associated with a more pronounced P3 wave. In contrast to previous ERP findings for the visual effect (Niedeggen et al., 2015; Niedeggen et al., 2004; Niedeggen et al., 2012), target detection in the auditory domain appears to be furthermore accompanied by an enhanced frontal negativity between 180 and 240 ms after onset. These results will be discussed in more detail below with respect to our research questions.

### 4.2 Question 1: Can we identify the behavioral characteristics of distractor-induced blindness in the auditory domain?

In line with our hypothesis, the presentation of target-like but irrelevant events (distractors) reduces the probability of having access to a target. The effect of multiple distractors on target detection is comparable with distractor-induced blindness found in vision.

The inhibitory effect of preceding distractors is also shared by Contingent Attentional Capture (CAC), which has been reported in the visual (Folk & Remington, 1998) and auditory

domain (Dalton & Lavie, 2004). Although both effects, DIB and CAC, presumably rely on a top-down activation of an inhibitory control mechanism (Folk et al., 1992; Lien et al., 2008; Niedeggen et al., 2015), prerequisites and behavioral consequences are different. The CAC is already elicited by the presentation of a single distractor in temporal proximity to the target, and affects the response time to this target (Folk et al., 1992). The DIB, however, requires the presentation of multiple distractor episodes and reduces the probability of detecting the target. These differences have already been highlighted in a previous study in the visual domain (Winther & Niedeggen, 2017b), and can be extended to the auditory domain. While both effects focus on top-down processes, they are in line with recent integrative models of attentional control (Awh et al., 2012), which emphasize that multiple selection influences determine stimulus priority.

Another related effect, the Attentional Blink (Raymond et al., 1992), has likewise been observed in the visual and auditory modality (e.g., (Shen & Alain, 2010; Tremblay et al., 2005)). Both, DIB and AB, share the characteristic that access to a (second) target stimulus is temporarily restricted. Moreover, target detection during the visual AB can reportedly be modulated by distractor-like events (Zhang et al., 2011). Importantly, the time courses of the effects differ: The expression of the visual AB, relying on the presentation of a single stimulus sequence, is largest if the SOA between two targets is about 200 – 500 ms (Dux & Marois, 2009). As opposed to this, the DIB is most pronounced at a cue-target SOA of 0 ms and gradually recovers within 200 ms (Niedeggen et al., 2015).

The different time courses of AB and DIB also seem to apply to the auditory domain. The auditory AB is mostly expressed at a T1-T2-SOA of 90 ms (Shen & Alain, 2010; Vachon & Tremblay, 2005) to 125 ms (Tremblay et al., 2005), and may persist up to 600 ms (Tremblay et al., 2005). This contrasts with the detection deficit during DID, which is significantly reduced at a cue-target SOA of 300 ms.

Finally, we have to consider the possible influence of switching costs between the auditory streams, which has been reported for verbal tasks (e.g., (Koch et al., 2011; Lin & Carlile, 2015)). As demonstrated in the superimposed streams condition of the behavioral

experiment, the DID effect was also observed if attentional switching between the channels was not necessary.

In sum, we found typical characteristics of the distractor-induced blindness in the auditory modality. In line with the hypothesis, the presentation of multiple distractors led to a significant deficit in target detection. Sharing the properties of the visual effect, distractor-induced deafness was more pronounced at a short cue-target SOA of 0 ms than at a longer 300 ms SOA. In line with our model of the visual DIB (Niedeggen et al., 2015) we assume that the inhibitory process induced by distractors is not immediately released with the onset of the cue. As in the visual domain, access to auditory target-like information is mostly restored within 300 ms.

#### **4.3 Question 2: Does the DID effect rely on a post-perceptual process?**

Target detection was accompanied by two ERP components: an increase in P3b amplitude and an increase in an early frontal negativity. Both effects will be discussed below.

The increase in P3b amplitude for detected targets is in line with our hypothesis, and has been observed in previous experiments on the visual DIB (Niedeggen et al., 2015; Niedeggen et al., 2004). Earlier AB studies already suggested that the P3b serves as a marker for conscious access in different modalities: Detection of the second target was characterized by an enhanced P3 component in the visual (Sergent et al., 2005; Vogel et al., 1998) and auditory modality (Shen et al., 2018). In line with a framework model of working memory (Soto & Silvanto, 2014), a reduced P3 amplitude observed for missed targets might signal that inter-areal communication processes related to the updating into working memory are not sufficiently triggered.

Although our current findings apparently support the idea that the P3b signals conscious access to an auditory target, we have to consider that a close link between P3 and conscious access has been disputed. Other studies suggested that the P3b might reflect a global violation of (auditory) regularities rather than conscious access, and that the posterior visual awareness negativity (VAN) may be a more valid psychophysiological correlate of visual awareness (Koch et al., 2016; Rutiku et al., 2015).

Our data also reveal that ERP effects preceding the P3b are associated with target access. As shown in Figure 3c, hits were accompanied by an increase in a frontal negativity around 200 ms. This preliminary effect cannot be attributed to sensory processing of the target characteristics (increase in amplitude): First, it was not observed for missed targets. Second, an analysis of the ERP effects induced by the final distractor (irrelevant increase in loudness) rather indicated that the sensory deviation elicits a later negativity with a different, more-central topography (see Supplement Figure S1, Table S1). Strikingly, Eklund and Wiens (2019) recently also observed an early negativity around 200 ms and a late positive component (LPC) as correlates of auditory consciousness in a threshold task.

In a first attempt to identify the functional role of this early ERP effect, we like to refer to a model of conscious auditory processing put forward by Näätänen et al. (2011), which focusses on three ERP components. The N1 peaking at 100 ms (Lange, 2013) was associated with onset detection and feature encoding of auditory stimuli (Näätänen et al., 2011). The mismatch negativity (MMN/N2a) - peaking about 150 - 250 ms - marks an updating of stimulus representations (Näätänen et al., 2011) triggered by a violated prediction. The processing negativity (PN/N2b) is a more sustained frontal component, and is regarded as endogenous and indicating top-down controlled, attentional stimulus selection (Näätänen et al., 2011; Tomé et al., 2015).

The early part of the frontal negativity observed in our study can hardly be classified as a N1 or MMN/N2a component because both reflect predominantly preconscious and automatic processes (Näätänen et al., 2011; Paavilainen, 2013), and therefore should also be expressed for missed targets. If the early frontal negativity observed in our study is further demonstrated to be a reliable ERP effect, we would like to suppose that it shares the characteristics of the (frontal) PN, which is associated with the activation of attentional control mechanisms enabling the maintenance of the attentional trace containing target features (Näätänen et al., 2011). We assume that in line with the model proposed by Näätänen et al. (2011), a corresponding process might also be crucial for target access in the DID paradigm: In case of a hit, the matching between the attentional trace containing

stored target features and the incoming stimulus features is successful. In case of a miss, the presentation of multiple distractors activates an inhibitory process, which is not fully released with the onset of the cue. Consequently, the activation of the target features by the attentional control system is delayed. This affects the matching process at an early, but not at a longer cue-target SOA.

As mentioned above, an early ERP correlate of auditory awareness has also been reported in recent research (Eklund et al., 2019; Eklund & Wiens, 2019). Notably, the “auditory awareness negativity” identified in these studies is shifted to central leads and has been linked to local recurrent processing in the auditory cortices. To identify the functional role of the early negativity in auditory awareness and to differ between theoretical accounts, further studies are necessary (see limitations below).

A deficit in attentional control, as assumed to be reflected by the frontal negativity, has not been observed for target processing in the visual domain. However, distractors drive a cumulative activation of a frontal process (Niedeggen et al., 2015; Niedeggen et al., 2012; Winther & Niedeggen, 2017a). Further studies will show whether a comparable mechanism can be identified in the auditory DID, and whether the activation triggered by the preceding distractors can be related to the expression of the early frontal negativity accompanying target access. Moreover, it remains to be explored whether the frontal negativity shares the characteristics of the N1 component observed in a previous auditory AB study (Shen & Alain, 2010). The central topography of the N1 component rather suggests that sensory processing is modulated in the auditory attentional blink.

To sum up, successful target detection was marked by a more pronounced P3b amplitude. However, conscious access to an auditory target apparently does not rely on this post-perceptual process alone. In contrast to the visual DIB, a frontal negativity might be related to the successful activation of a control mechanism, which could support the (re-) allocation of attention following the presentation of multiple task-irrelevant distractors.

#### **4.4 Limitations and future research**

Discussing our results, the following limitations have to be considered:

First, the DID effect we observed was considerably smaller (difference between 0 and multiple distractors: 23% in behavioral study, 8% in ERP study) than the visual DIB effect (>45% in Winther and Niedeggen (2017a) for color targets, ~20% in Michael et al. (2011) for motion and orientation targets). The frequency of false alarms also differed, being higher in the DID (mean of 11.1% in behavioral study, 25.4% in ERP study) as compared to DIB studies (e.g., mean of 2.5 – 8.8% in Winther and Niedeggen (2017a)). Future research is necessary to determine why the response bias is shifted in the auditory experiments, and whether this effect can be related to the experimental design.

Second, we have to consider that ERP differences between “hits” and “misses” might not only reflect differences in conscious access to a target stimulus, but also differences in decisional processes. Although we requested an explicit report in each perceptual state (target perceived vs. not perceived), this problem still might affect our study. Based on recent research on perceptual choice confidence (Lim et al., 2020), we assume that the early frontal negativity is unlikely to be affected by decisional processes. However, we cannot rule out that the expression of the P3b amplitude is modulated by subjective confidence (Ye et al., 2019). Further experiments on the DID therefore will have to consider the factor ‘confidence’.

Third, while frontal negativity and P3 were both linked to successful target detection, the functional relation between the components remains unknown. Further studies will have to show whether access to the target in the auditory domain critically depends on the activation of **both** processes indicated by the ERP components. Importantly, the early effect we observed was not defined in an a priori hypothesis and should therefore be classified as preliminary finding, which requires replication.

Fourth, our study does not allow us to track the activation driven by multiple distractors. An upcoming study will show whether a cumulative inhibition process can be observed – as previously reported in the visual DIB (Niedeggen et al., 2015; Niedeggen et al., 2012).

Fifth, we measured cue and target detection using a binary task, and did not assess subjective audibility ratings. It has been debated for the visual AB whether subjective visibility

of the target is distributed bimodally in an “all-or-none”-fashion (Sergent et al., 2005; Sergent & Dehaene, 2004) or rather gradually (Nieuwenhuis & de Kleijn, 2011). Pincham et al. (2016) recently suggested a dissociation between subjective visibility and target report accuracy for the visual AB. Future research could examine the relation between target detection and subjective audibility for the auditory DID effect.

Finally, we have to consider the strong variability of the behavioral DID effect (range of misses: 0 - 87%). As proposed in previous AB studies, inter-individual differences might arise from differences in executive working memory functioning (Willems & Martens, 2016). This aspect should be followed up in further studies.

#### **4.5 Conclusion**

Our findings provide evidence for a deficit in auditory target detection induced by multiple distractors (distractor-induced deafness; DID). The current study extends previous research by replicating the characteristics of the visual distractor-induced blindness effect in the auditory modality. In both modalities, multiple target-like distractors appear to activate a negative attentional set. Due to this inhibition, access to target-line features is restricted.

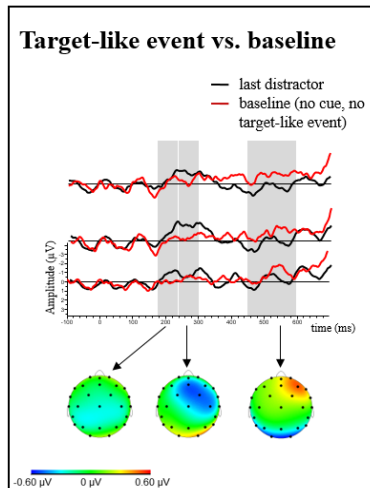
In the auditory domain, this restriction is not only related to the expression of the P3b amplitude, but also to the expression of a frontal negativity. This modality-specific effect might signal the release of distractor-induced inhibition, and the recovery of attentional control.



## Supplementary material Study I

## Supplement 1: Last distractor vs. baseline

Figure S1



*Note.* Grand-averaged ERP waveforms for a baseline condition (red line: ERP activity driven by rapid serial auditory stimulation – but excluding cue, target or distractors onset) and distractor-driven activity (black line: ERP elicited by final distractor in a multiple distractor condition). Reference-independent topographic distributions for three time windows (180 – 240 ms, 240 – 300 ms, 450 – 600 ms) are presented below the grand-averages.

Table S1

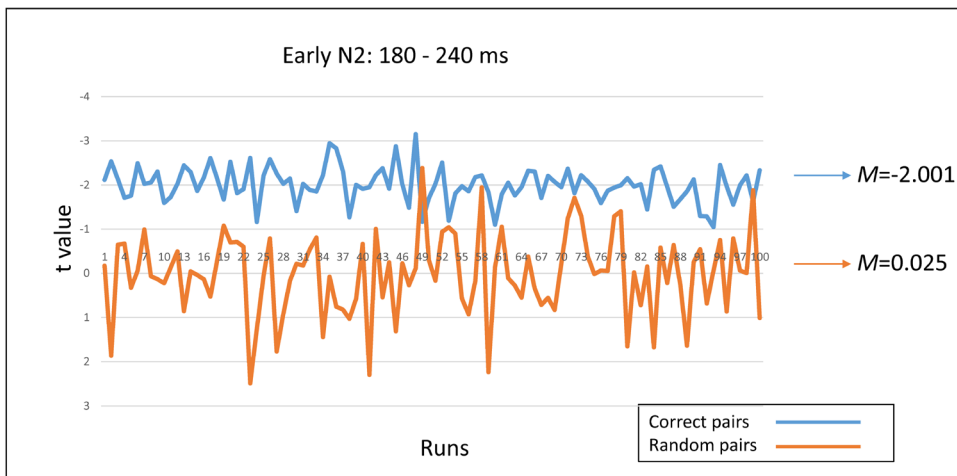
ERP component	last distractor vs. baseline (frontal Cluster)
early negativity (180 - 240 ms)	$F(1, 30) = 2.01, p = .167, \eta = .063$
late negativity (240 - 300ms)	$F(1, 30) = 2.61, p = .117, \eta = .080$

*Note.* Statistical differences between ERP elicited by rapid serial auditory presentation (excluding cue, target, or distractor onset) and distractor-evoked ERPs. Analysis was focused on the two time ranges of the frontal negativity (early, late), and considered the frontal electrode cluster. In the two consecutive time windows, no statistically significant difference was observed.

**Supplement 2: Results of the randomization tests**

**Figure S2.1**

*Randomization test for the early negativity (anterior cluster)*



*Note.* Results of the randomization test for the early negativity (180 - 240 ms) and the anterior electrode cluster. The blue line indicates t-values for correct pairings, i.e., hits vs. misses for each of the subsamples of 24 randomly selected participants. The orange line shows t-values for the same subsamples of subjects, where assignment of hits and misses was switched for 12 pairs within the subsample and kept for the other 12. Mean values on the right represent mean t-values over 100 randomizations for both random and correct pairings. Correct pairs showed substantially larger t-values than random pairs.

**Figure S2.2**

*Randomization test for the P3 (posterior cluster)*



*Note.* Results of the randomization test for the P3 (480 - 540 ms) and the posterior electrode cluster. The blue line indicates t-values for correct pairings, i.e., hits vs. misses for each of the subsamples of 24 randomly selected participants. The orange line shows t-values for the same subsamples of subjects, where assignment of hits and misses was switched for 12 pairs within the subsample and kept for the other 12. Mean values on the right represent mean t-values over 100 randomizations for both random and correct pairings. Correct pairs showed substantially larger t-values than random pairs.

### Supplement 3: Descriptive statistics for reference-independent values in the 10 time windows

Table S3

Electrode Cluster	0 - 60 ms	60 - 120 ms	120 - 180 ms	180 - 240 ms	240 - 300 ms	300 - 360 ms	360 - 420 ms	420 - 480 ms	480 - 540 ms	540 - 600 ms
anterior	M = .013 95% CI [-.11, .13]	M = .023 95% CI [-.17, .21]	M = .128 95% CI [-.04, .29]	M = -.567 95% CI [-.78, -.35]	M = -1.042 95% CI [-1.29, -.75]	M = -.106 95% CI [-.43, .22]	M = .714 95% CI [.38, 1.05]	M = .482 95% CI [.08, .89]	M = .420 95% CI [.09, .75]	M = .168 95% CI [-.16, .49]
	M = .039 95% CI [-.06, .14]	M = -.025 95% CI [-.17, .12]	M = -.030 95% CI [-.17, .11]	M = .286 95% CI [.10, .47]	M = .663 95% CI [-.46, .87]	M = .257 95% CI [-.01, .53]	M = -.207 95% CI [-.43, .06]	M = .033 95% CI [-.29, .36]	M = .140 95% CI [-.12, .40]	M = .436 95% CI [.20, .67]

*Note.* Mean amplitudes (in  $\mu\text{V}$ ) and 95% confidence intervals (CIs) of the Mean after presentation of the Cue-target compound, reported for the consecutive ten time windows. The reference-independent ERP data reported here are collapsed for hits and misses in the multiple distractor condition.

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## CHAPTER 4

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

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This chapter is based on the following published original article:

Kern, L., & Niedeggen, M. (2021). ERP signatures of auditory awareness in cross-modal distractor-induced deafness. *Consciousness and Cognition*, 96, 103241.

<https://doi.org/10.1016/j.concog.2021.103241>

*In accordance with copyright regulations, the full text of this original article is not included in the online version of this dissertation.*

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## CHAPTER 5

### Are auditory cues special? Evidence from cross-modal distractor-induced blindness

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This chapter is based on the following original article:

Kern, L., & Niedeggen, M. (submitted). Are auditory cues special? Evidence from cross-modal distractor-induced blindness.

Preprint doi: <https://www.doi.org/10.31234/osf.io/6tfx9>

### Abstract

A target that shares features with preceding distractor stimuli is less likely to be detected due to a distractor-driven activation of a negative attentional set. This transient impairment in perceiving the target (distractor-induced blindness/deafness) can be found within vision and audition. Recently, the phenomenon was observed in a cross-modal setting involving an auditory target and additional task-relevant visual information (cross-modal distractor-induced deafness). In the current study, consisting of three behavioral experiments, a visual target, indicated by an auditory cue, had to be detected despite the presence of visual distractors. Multiple distractors consistently led to reduced target detection if cue and target appeared in close temporal proximity, confirming cross-modal distractor-induced blindness. However, the effect on target detection was reduced compared to the effect of cross-modal distractor-induced deafness previously observed for reversed modalities. The physical features defining cue and target could not account for the diminished distractor effect in the current cross-modal task. Instead, this finding may be attributed to the auditory cue acting as an especially efficient release signal of the distractor-induced inhibition. Additionally, a multisensory enhancement of visual target detection by the concurrent auditory signal might have contributed to the reduced distractor effect.

**Keywords:** distractor-induced blindness, attention, cross-modal perception, inhibition, multisensory enhancement

## 1. Introduction

In our daily lives, we are constantly surrounded by a vast number of stimuli deriving from different sensory modalities. The perceptual system with its limited capacity has to filter the incoming information and efficiently select stimuli relevant to the current task, while irrelevant, distracting stimuli need to be inhibited (Feldmann-Wüstefeld & Vogel, 2019; Hasher et al., 2007; Moher et al., 2014). In addition to bottom-up stimulus properties, this selection and inhibition is assumed to be controlled top-down by *attentional sets* (Desimone & Duncan, 1995; Olivers & Meeter, 2008). While target features are stored in positive attentional sets, or target templates, which enhance processing of stimuli matching this template (Dombrowe et al., 2011; Leber & Egeth, 2006), negative attentional sets, or distractor templates, contain features that attention is directed away from (Arita et al., 2012; Olivers & Watson, 2006; Woodman & Luck, 2007; Zhang et al., 2009). The features of target and distractors are not always distinct but can overlap, leading to impaired target processing if a negative attentional set containing these shared features is activated (Boncompagni & Cosmelli, 2018; Folk et al., 2008; Lleras et al., 2008; Sahraie et al., 2001; Wu & Fu, 2017).

One experimental paradigm demonstrating the consequences of a negative attentional set comprising shared features of distractors and target on target detection is *distractor-induced blindness* (DIB). In the DIB task, participants shall detect a target (e.g., episode of coherent motion in random dot kinematogram) that is indicated by a cue (e.g., color change of fixation to red) (Sahraie et al., 2001). In the visual modality, it was observed consistently that target-like, but task irrelevant events (i.e., distractors) occurring before the cue are associated with a transient deficit in detecting the target. This “blindness” is most pronounced if cue and target are displayed simultaneously and vanishes at a cue-target stimulus onset asynchrony (SOA) of 200 – 300 ms (Hesselmann et al., 2006; Sahraie et al., 2001; Winther & Niedeggen, 2018). The DIB effect has been attributed to a central inhibition of distractor (and therefore target) features, building up cumulatively with the repeated presentation of to-be-ignored distractors (Niedeggen et al., 2015; Niedeggen et al., 2012;

Winther & Niedeggen, 2017b). Within this model, the cue is working as a release signal of the inhibition, leading to a gradual deactivation of the negative attentional set and recovering target detection rates with longer cue-target-SOAs (Michael et al., 2011). A higher selection difficulty of the cue due to lower salience is associated with a larger DIB effect (Hay et al., 2006). Previous research ruled out that DIB can be accounted for by spatial shifts of attention between the two visual streams containing cue and target (Hesselmann et al., 2009).

To date, DIB has been observed for the features motion, orientation and color (Michael et al., 2011; Winther & Niedeggen, 2017a). Some models of attentional control assume that inhibition of irrelevant stimuli works in a similar fashion for different visual features (Hasher et al., 2007; Olivers & Meeter, 2008). This assumption is supported by neuroimaging studies suggesting that working memory processes including inhibition do not seem to be organized by stimulus type (for a meta-analysis: (Wager & Smith, 2003)). Interestingly, one difference between visual features was demonstrated for DIB: color changes are apparently more effective in eliciting the inhibitory process than motion stimuli (Winther & Niedeggen, 2017a; Winther & Niedeggen, 2018). This finding might be attributed to differences between ventral and dorsal stream processing (Winther & Niedeggen, 2017a), with color being predominantly processed in the ventral and motion/orientation being primarily associated with the dorsal visual system (e.g., (Kravitz et al., 2013; Valyear et al., 2006)). The distinction between ventral and dorsal processing has been proposed to not only apply to perceptual processing stages but also to working memory selection (Nee et al., 2013).

The effect of distractors on target detection is not restricted to the visual modality. Recent studies revealed a *distractor-induced deafness* (DID) (Kern & Niedeggen, 2021a), which can also be observed under cross-modal stimulation (Kern & Niedeggen, 2021b). In the previous cross-modal set-up (Kern & Niedeggen, 2021b), the cue was presented in a rapid serial visual presentation (RSVP) sequence and the target occurred in an auditory stream. The visual sequence consisted of a circular presentation of eight greyscale bars,



giving the impression of a circular movement ('preloader' symbol). A small white circle with black outline could appear at the position of one of the bars, defining the cue. The target was a short rise in amplitude in a continuous tone occurring with or after the cue, while rises in amplitude before the cue were distractors that ought to be ignored. In accordance with unimodal findings, multiple distractors impaired target detection, especially if cue and target appeared concurrently. Interestingly, DID in both uni- and cross-modal setting was associated with a smaller decrease in target detection compared to the visual modality. However, the DIB effect remained to be examined for the combination of auditory cue and visual target.

The processing and detection of target stimuli in a *multisensory*, or *cross-modal*, environment is in addition to attentional selection and inhibition processes observed within modalities also influenced by interactions between the senses (Koelewijn et al., 2010; Spence et al., 2009; Stein & Stanford, 2008). If two stimuli from different modalities overlap in presentation time and/or spatial location, performance enhancements (i.e., *multisensory enhancement*) can often be observed compared to unimodal settings (Klapetek et al., 2012; Stein & Stanford, 2008; Stevenson et al., 2014; Talsma et al., 2010; Tang et al., 2016). Previous research demonstrated that an auditory stimulus temporally coinciding with a visual target can cause an enhancement of perceived visual stimulus intensity (Noesselt et al., 2008; Stein et al., 1996) and of target detection rates (Andersen & Mamassian, 2008; Frassinetti et al., 2002; Giard & Peronnet, 1999; Gleiss & Kayser, 2013; Lippert et al., 2007; Noesselt et al., 2010; Van der Burg et al., 2011). Therefore, potential influences of multisensory processing need to be considered in cross-modal settings.

The current study comprises three consecutive behavioral experiments that aimed to investigate whether the characteristics of distractor-induced blindness can be observed in a cross-modal setting. Here, the cue as signal of task relevance was defined in the auditory modality, while target and distractors were visual stimuli. More specifically, the following two characteristics should be examined: (1) are multiple target-like distractors associated with

impaired target detection compared to zero and one distractor conditions?, and (2) is the target detection impairment after multiple distractors most pronounced at a cue-target-SOA of 0 ms and decreases with increasing SOA? If a cross-modal DIB effect with these characteristics can be stated, this in combination with previous findings (Kern & Niedeggen, 2021a, 2021b) speaks for DIB/DID occurring independent of the sensory modality cue and target are presented in. However, we also aimed to observe whether the modality cue and target appear in might have an impact on the expression of the distractor effect. Uni- and cross-modal DID showed a similar magnitude and appeared to be smaller than the visual DIB (Kern & Niedeggen, 2021a, 2021b). One possible reason for this observation could be that auditory distractors generally have a weaker influence on target processing, possibly due to differences in distractor processing between visual and auditory domain. If we find a cross-modal DIB of comparable size as the unimodal visual effect – therefore being larger than DID – this speaks for a larger impact of distractors on target detection in the visual compared to the auditory modality.

## 2. EXPERIMENT I

The aim of Experiment I was to examine whether two basic characteristics of distractor-induced blindness - the effect of multiple distractor episodes and the recovery of this effect as a function of the cue-target-SOA - can be found in a cross-modal setting with the cue embedded in an auditory and distractor/targets occurring in a visual stream. So far, such a distractor effect (distractor-induced blindness/deafness) has been shown within the visual (Sahraie et al., 2001) and auditory modality (Kern & Niedeggen, 2021a) and was recently also observed in a cross-modal task for a visual cue and an auditory target (Kern & Niedeggen, 2021b). In all of these settings, the largest distractor effect occurred at a cue-target-SOA of 0 ms and decreased with increasing SOA. It remained to be examined if this effect also occurs in a cross-modal set-up containing a visual target.

The current study aimed to close this research gap by investigating cross-modal distractor-induced blindness with the cue as signal of task relevance being defined in the auditory modality (i.e., short rise in amplitude in a continuous tone) and target and distractors being visual stimuli (i.e., brief appearance of a small white circle). We expected to observe a decrease in target detection following the presentation of multiple distractors. The target detection deficit should be most pronounced if cue and target occur concurrently and should recover with increasing cue-target-SOA. According to the DIB model, the transient “blindness” for the target is caused by the activation of a central inhibitory process by the distractors (Hesselmann et al., 2006; Niedeggen et al., 2015). Thus, one would assume that target detection should also be impaired in this cross-modal setting, irrespective of the cue being presented in another modality. To estimate the expression of the distractor-induced effect on target detection, the acquired data of Experiment I were compared to a previous behavioral experiment with visual cue and auditory distractors and target (Kern & Niedeggen, 2021b). If auditory distractors have a weaker influence on target detection than visual distractors, cross-modal DIB should show a larger magnitude than cross-modal DID.

## 2.1 Method

The data, code and stimulus material of all three experiments, which were not pre-registered, are provided in an open repository (<https://www.doi.org/10.17632/wxmhwv7xvd.1>).

### 2.1.1 Participants

Sample sizes were calculated *a priori* using G\*Power (Faul et al., 2007) for  $\alpha = .05$  and an intended power of 80% (F-Test with repeated measurement). Based on a previous cross-modal study (Kern & Niedeggen, 2021b), we expected a large effect ( $f = .40$ ) for the within-subject factor ‘number of distractors’ (1 vs. multiple distractors). This resulted in a required sample size of  $N = 15$  for each of the three experiments.

Throughout Experiments I-III, participants had no history of neurologic or psychiatric conditions, normal or corrected-to-normal visual acuity and self-reported normal hearing ability. Participants were recruited in the university environment, received course credit or 10€/hour for participation and gave written informed consent prior to testing. The experimental procedure (including Experiments I-III) was approved in advance by the ethics committee of Freie Universität Berlin (027/2019). A priori defined exclusion criteria based on previous studies (Kern & Niedeggen, 2021b) were as follows: (1) unreliable task performance during pretest trials (< 60% correct target detection); (2) unreliable task performance during the experiment (< 25% hit rate in zero distractor condition at SOA 0 ms).

Eighteen healthy subjects participated in Experiment I (13 women; 20 – 35 years of age;  $M_{age} = 25.61$ ,  $SD = 5.25$ ). No participant had to be excluded based on the exclusion criteria. The data of Experiment I were compared to a previous behavioral data set (N = 20; 13 women; 18 – 39 years of age;  $M_{age} = 29.20$ ,  $SD = 5.92$ ), which examined cross-modal distractor-induced deafness and was published as part of Kern and Niedeggen (2021b).

### **2.1.2 Stimuli, procedure and design**

All visual and auditory stimulus material used in Experiment I was taken from previous experiments (Kern & Niedeggen, 2021a, 2021b). The resulting analogy in the set-up allowed a statistical comparison of the current data to a previous data set.

The experiment was conducted in a sound-attenuated chamber with dimmed and indirect lighting. Participants sat at 62 cm viewing distance in front of a 20" monitor (Sony Trinitron Multiscan G520) and wore in-ear headphones (Audio-Technica ATH-LS70iS) with individually fitted earpieces. Auditory stimuli were created and edited with the programs "Tone Generator" and "WavePad Editor" (NCH Software, Greenwood, USA). The experiment was run on a Windows PC using PsychoPy (Version 3.6.8 for Windows).

Participants heard two auditory sequences and monitored a dynamic visual stream concurrently. Trial duration was set to 5,000 ms. The two rapid serial auditory presentations

(RSAPs) were each presented to one ear. On the right ear, a continuous tone with a modulation at 5 Hz in a frequency range from 270 – 330 Hz was played (stream 1). The auditory cue was defined in this sequence as a transient rise in amplitude (+10 dB) for 100 ms. The cue was presented at a randomized temporal position between 3,100 – 4,000 ms after trial onset. On the left ear, participants heard a second sequence consisting of 50 sine-wave tones (duration: 30 ms, inter stimulus interval: 70 ms) that were each randomly selected from a set of seven tones (frequency range 1,800 – 2,200 Hz; stream 2). The amplitude of the continuous tone was reduced compared to the sine-wave tone sequence (-20 dB). Presentation time of the sine-wave tones was 30 ms with a 70 ms inter-stimulus interval (ISI) between tones. In this second RSAP stream, no task-relevant event occurred. For the aim of comparability between current and previous cross-modal findings, we kept both auditory streams in the experimental set-up since removal of one of the RSAP sequences could affect task difficulty.

Simultaneous to the two auditory sequences, a rapid serial visual presentation (RSVP) was displayed at the center of the screen. Eight bars were arranged in a circle with a total retinal size of  $1.66^\circ$  in diameter. The impression of a clockwise motion was created by varying the luminance of adjacent bars, in analogy to the signal indicating a loading process in software or websites ('preloader' symbol). The lightest bar was colored in white and thus appeared to be missing, while the darkest bar was colored in black. Changes in luminance appeared each 100 ms with no ISI. Target and distractors were defined within this RSVP sequence: a small white circle with black outline ( $0.186^\circ$  in diameter) could appear for 100 ms at the position of the missing bar in the preloader symbol. The occurrence of a small white circle at the same time with or following the auditory cue was defined as target. Small circles appearing before cue onset were labeled as distractors and should be ignored. Stimulus onset asynchrony (SOA) between onset of the last distractor and cue was at least 500 ms. SOAs between distractors were set between 200 to 700 ms. The experimental set-up is depicted in Figure 1.

After giving informed consent, testing started with 32 pretest trials, during which participants were familiarized with stimuli and task. The experimenter provided verbal feedback on the correctness of responses after each trial. If participants showed a good understanding of instructions and a reliable target detection during at least 60% of trials, the main experiment started. If task performance remained unreliable during pretest, testing was aborted (see exclusion criterion 1).

The experiment consisted of 290 trials, which were presented in randomized order for each participant. After each trial, participants had to decide whether they perceived an auditory cue (question 1: "Did you hear a change in the continuous tone?") and whether they saw a target accompanying or following the cue (question 2: "Did you see a small white circle simultaneous to or after a change in the continuous tone?"). Non-speeded responses (yes/no) were given via button press on the keyboard. Participants were instructed to answer as accurately as possible. The experiment lasted approximately one hour.

Targets could appear at the same time as or shortly after the cue (within-subject factor cue-target-SOA: 0 ms vs. 100 ms vs. 300 ms). Additionally, the number of visual distractors preceding cue and target was manipulated as second within-subject factor (0 vs. 1 vs. 6-8 distractors). For each SOA condition, 80 trials containing cue and target were presented. Within each of the three SOA conditions, 40 trials included multiple distractors, 20 trials had one distractor, and 20 trials comprised no distractors. To be able to assess the reliability of response behavior in terms of false alarms (falsely reported target after correctly detected cue), trials only containing the cue were added as a control condition (15 trials with multiple distractors, 15 trials without distractor). As a second control conditions, 20 trials did not include a relevant stimulus (10 trials with multiple distractor, 10 trials without distractors).

The previous behavioral study, which examined cross-modal distractor-induced deafness and was compared to the results of Experiment I, had used the identical auditory and visual streams, task-relevant stimuli and experimental manipulations. Therefore, sensory stimulation was identical and solely the assignment of cue and target to the sensory

modalities was reversed (i.e., cue: appearance of small white circle; distractors/target: short rise in amplitude in continuous tone). The data of this previous experiment are accessible in an open repository (<https://doi.org/10.17632/6n7585w2jj.1>).

### **2.1.3 Data analysis**

The hit rate (i.e., correct target detection after correctly detected cue) was computed for each experimental condition and each participant. Behavioral data were analyzed using IBM SPSS Statistics 27 in a two-way repeated measures ANOVA including the within-subject factors 'SOA' between cue and target (0 ms vs. 100 ms vs. 300 ms) and 'number of distractors' (0 vs. 1 vs. 6-8). Bonferroni-corrected post-hoc comparisons were computed in case of a significant main effect or interaction. Greenhouse-Geisser corrections were applied if appropriate. If the interaction 'SOA' x 'number of distractors' reached significance, post-hoc tests were conducted for each SOA to examine an influence of the number of distractors, and the hit rates in the multiple distractor condition were compared between the three SOAs to assess the recovery of hit rates.

In a second, additional step of analysis, the data acquired in Experiment I were compared to previous cross-modal behavioral data for reversed modalities (Kern & Niedeggen, 2021b) to assess a possible impact of the cross-modal setting. To this aim, an ANOVA with the repeated-measures factor 'number of distractors' (0 vs. 1 vs. 6-8) and the between-subject factor 'cross-modal setting' (auditory cue, visual target (Exp. I) vs. visual cue, auditory target) was conducted, focusing solely on the cue-target-SOA of 0 ms.

## **2.2 Results**

Mean target detection rates for Experiments I-III are presented in Table 1. The results of Experiment I are depicted in Figure 1. Participants showed a reliable response behavior, as demonstrated by overall high hit rates and few false alarms (multiple distractors:  $M = 3.48\%$ ,  $SD = 9.27$ ; without distractors:  $M = 2.47\%$ ,  $SD = 8.13$ ). Occurrence of false alarms was not influenced by the presence of distractors,  $F(1, 17) = .95$ ,  $p = .343$ ,  $\eta_p^2 = .053$ .

Furthermore, cue detection was reliable ( $M = 95.69\%$ ,  $SD = 5.80$  for multiple distractors, SOA 0 ms), indicating a high salience of the cue.

The main effect of number of distractors reached significance,  $F(1.15, 19.58) = 10.56$ ,  $p = .003$ ,  $\eta_p^2 = .283$ . Post-hoc comparisons showed that hit rates decreased with increasing number of distractor events (0 vs. multiple distractors:  $F(1, 17) = 11.48$ ,  $p = .003$ ,  $\eta_p^2 = .403$ ; 1 vs. multiple distractors:  $F(1, 17) = 14.53$ ,  $p = .001$ ,  $\eta_p^2 = .461$ ; 0 vs. 1 distractor:  $F(1, 17) = 6.08$ ,  $p = .025$ ,  $\eta_p^2 = .263$ ).

The SOA between cue and target had no significant effect,  $F(2, 34) = 1.28$ ,  $p = .291$ ,  $\eta_p^2 = .070$ . Instead, the interaction between “number of distractors” and “SOA” reached significance,  $F(4, 68) = 4.03$ ,  $p = .005$ ,  $\eta_p^2 = .192$ , indicating that distractors influenced hit rates differently at the three SOAs. Post-hoc tests revealed a significant effect of number of distractors on target detection at short cue-target intervals (SOA 0 ms:  $F(1.24, 21.01) = 13.72$ ,  $p = .001$ ,  $\eta_p^2 = .447$ ; SOA 100 ms:  $F(2, 34) = 6.27$ ,  $p = .005$ ,  $\eta_p^2 = .270$ ), while this influence was extinguished at SOA 300 ms ( $F(2, 34) = .40$ ,  $p = .673$ ,  $\eta_p^2 = .023$ ). Additionally, post-hoc tests showed a significant recovery of target detection rates with increasing SOA for the multiple distractor condition,  $F(2, 34) = 7.38$ ,  $p = .002$ ,  $\eta_p^2 = .303$ , following a linear trend,  $F(1, 17) = 12.09$ ,  $p = .003$ ,  $\eta_p^2 = .416$ .

### **Comparison between two cross-modal data sets: does the cross-modal setting influence the distractor effect?**

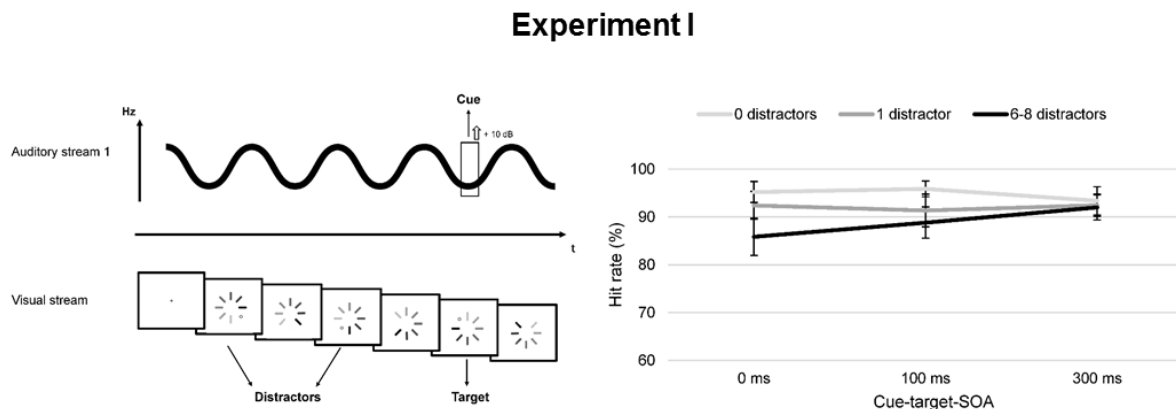
In a following analysis step, the data from Experiment I and a previous cross-modal experiment with identical experimental set-up but reversed modalities regarding cue and target were jointly analyzed to examine an effect of cross-modal setting. Hit rates in both experiments at SOA 0 ms are displayed in Figure 2. The analysis revealed a significant main effect of cross-modal setting,  $F(1, 36) = 9.35$ ,  $p = .004$ ,  $\eta_p^2 = .206$ , driven by higher hit rates in Experiment I ( $M = 91.16\%$ , 95% CI [83.97, 98.35]) than in the previous experiment with visual cue and auditory target ( $M = 76.22\%$ , 95% CI [69.41, 83.04]). Additionally, the interaction between ‘number of distractors’ and ‘cross-modal setting’ at cue-target-SOA 0 ms



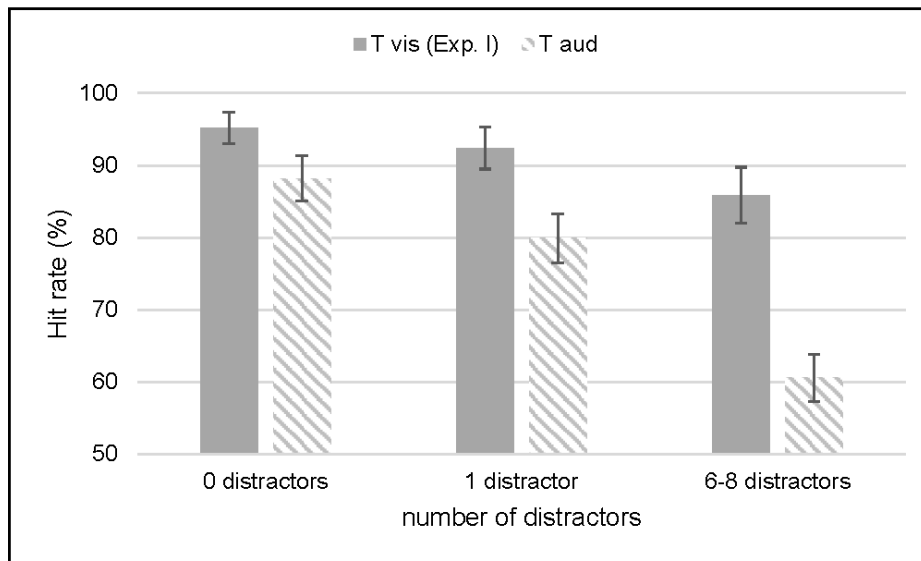
yielded significance,  $F(2, 72) = 6.54$ ,  $p = .002$ ,  $\eta_p^2 = .154$  (main effect number of distractors:  $F(2, 72) = 26.89$ ,  $p < .001$ ,  $\eta_p^2 = .428$ ). Post-hoc tests for each distractor condition showed no significant difference in hit rates if no distractors were presented,  $F(1, 36) = 3.24$ ,  $p = .080$ ,  $\eta_p^2 = .083$ , while higher hit rates were observed in Experiment I if distractors were present (1 distractor:  $F(1, 36) = 4.53$ ,  $p = .040$ ,  $\eta_p^2 = .112$ , multiple distractors:  $F(1, 36) = 13.16$ ,  $p < .001$ ,  $\eta_p^2 = .268$ ).

**Figure 1**

*Task design and results of Experiment I*



*Note.* The left panel illustrates the task design: The cue was defined in the auditory modality, while target and distractors were presented embedded in a visual RSVP sequence. Target and distractor stimuli solely differed in the timing of their presentation: distractors appeared before cue onset, while a target could occur at the same time as or after the cue. The 'preloader' symbol at the center of the screen changed every 100 ms, creating the impression of a clockwise motion. On the left ear, participants always heard a sequence of pure tones, while on the right ear a continuous tone was presented. In Experiment I, the cue was a short rise in amplitude (+10 dB) in the continuous tone. The target event was the appearance of a small white circle within the preloader symbol for 100 ms simultaneous to or after the cue. The right panel shows the results of Experiment I: Mean hit rates (in %; y-axis) are depicted for the three SOA conditions (x-axis) and the number of distractors. Error bars depict standard errors of the mean. Multiple distractors were associated with lower target detection rates at short cue-target-SOAs.

**Figure 2***Distractor effects at cue-target-SOA 0 ms in two cross-modal settings*

*Note.* Hit rates acquired in Experiment I in comparison to hit rates from a previous cross-modal experiment (Kern & Niedeggen, 2021b) at cue-target-SOA 0 ms. Both experiments had an identical set-up and sensory stimulation, and solely differed in the assignment of cue and target/distractors to sensory modalities. While target and distractors were visual and the cue auditory in Experiment I, auditory distractors and target and a visual cue were presented in the previous study. Overall, hit rates were higher if the cue was auditory and the target visual (Experiment I). A significant interaction between number of distractors and cross-modal setting could be observed, indicating a more pronounced drop of hit rates after the presentation of distractors if the target was auditory.

**2.3 Discussion**

Experiment I demonstrated that a visual target presented concurrently with or shortly after an auditory cue is less reliably detected if it is preceded by multiple target-like distractors. As hypothesized, target detection was most impaired at a cue-target-SOA of 0 ms. In line with the time course observed within the visual modality (Michael et al., 2011; Sahraie et al., 2001), the effect vanished at SOA 300, indicating the deactivation of the distractor template. Therefore, cross-modal distractor-induced blindness with the typical behavioral characteristics can be stated, providing evidence that a distractor effect cannot only be found within visual and auditory modality but also in both possible combinations between these modalities. The finding implies that target detection is reduced at SOA 0 ms in a cross-modal setting if a negative attentional set is activated by the repeated presence of

multiple distractors in the auditory and visual domain. The release of this inhibition of visual features shows comparable properties for a visual and auditory cue.

Additionally, and in extension of previous research, the results of Experiment I demonstrate that DIB can also be elicited for the appearance of a small shape, which was associated with a local change in luminance. Consequently, a fourth visual feature could be established, which further strengthens the replicability of the DIB effect across different feature dimensions and speaks for a similar functioning of the inhibitory process for a variety of visual features.

While a substantial detection deficit for the visual target after multiple distractors and at short SOAs could be found, the size of the effect (i.e., zero – multiple distractors at SOA 0 ms) was smaller than usually observed within the visual modality (Niedeggen et al., 2012; Winther & Niedeggen, 2017a). Furthermore, the comparison with a cross-modal data set from a previous study with a reversed assignment of modalities revealed that hit rates were higher if the cue was auditory and distractors and target occurred in the visual modality than vice versa. Importantly, the effect of distractors on target detection was more pronounced for cross-modal DID than for cross-modal DIB (see Figure 2), indicating a greater susceptibility to distractors in case the cue was visual and the target and distractors auditory. This finding contradicts the assumption of a generally larger effect of visual compared to auditory distractors on the detection of a target in the same modality. That the cross-modal distractor effect appears to be reduced compared to the unimodal visual effect might be attributed to an enhancement of visual target processing by a concurrent auditory cue, which has been demonstrated for other paradigms (Frassinetti et al., 2002; Noesselt et al., 2008; Noesselt et al., 2010; Van der Burg et al., 2011; Zhao et al., 2020). This multisensory enhancement might counteract the distractor-induced inhibition to a certain degree. However, an alternative explanation could be that the cue feature rise in amplitude - and therefore a brief increase in loudness of the task relevant auditory stream - might have been especially efficient in releasing the distractor-evoked inhibition and in redirecting attention to the visual target.

### 3. EXPERIMENT II

Sounds with increasing intensity in terms of loudness (i.e., 'looming sounds') can enhance neural excitability of low-level visual areas (Romei et al., 2009), as well as visual orientation sensitivity (Cecere et al., 2014; Leo et al., 2011) compared to sounds of constant intensity. Additionally, looming auditory stimuli have been associated with preferential processing during multisensory integration (Cappe et al., 2012; Sutherland et al., 2014) and are claimed to be very salient since they increase phasic alertness (Bach et al., 2009) and activate a distributed brain network associated with attentional processes (Seifritz et al., 2002). If a comparable process is triggered during cross-modal DIB, one could assume that the auditory cue characteristics affect the detectability of the target. Thus, the increase in loudness as cue might have triggered a fast attentional allocation to the target stream and could have initiated a more efficient release of the negative attentional set than a tone of constant intensity.

To test if the cross-modal DIB effect observed in Experiment I is influenced by the feature defining the auditory cue, Experiment II was conducted. This subsequent experiment included the identical visual RSVP stream containing target and distractors and the same auditory stimulation, except for a different auditory feature - frequency composition - now defining the cue. We expected to replicate the cross-modal DIB effect from Experiment I. If a rise in amplitude as cue is an especially efficient release signal, the observed distractor effect at SOA 0 ms is expected to be larger in Experiment II compared to Experiment I. For visual stimuli, previous studies that experimentally manipulated cue salience indicated that a more salient cue is associated with a smaller DIB (Hay et al., 2006). To test for potential differences in cue salience, cue detection rates were assessed and compared between both experiments.

#### 3.1 Method

##### 3.1.1 Participants

Twenty-one new participants, who did not participate in Experiment I, were tested in Experiment II. The same requirements, exclusion criteria and a priori power analysis outlined in section 2.1.1. applied for Experiment II. One participant had to be discarded due to fulfilling the second exclusion criterion. The final sample consisted of 20 participants (12 women; 18 – 35 years of age;  $M_{age} = 25.59$ ,  $SD = 4.46$ ).

### **3.1.2 Stimuli, procedure and design**

Stimuli, experimental procedure and task were identical to Experiment I except for the feature defining the auditory cue. In this experiment, the cue was now embedded in stream 2 consisting of sine-wave tones. A deviant tone could appear at one point in this sequence, which consisted of an overlay of two pure tones (1,600 and 2,400 Hz; duration: 30 ms). This deviant tone served as cue. The same auditory cue has been applied in a previous study on the unimodal DID effect (Kern & Niedeggen, 2021a). Importantly, the amplitude of the cue – and therefore its perceived loudness – was matched to the amplitude of all other tones in the RSAP sequence. Thus, the cue was solely defined by the frequency composition. The cue did appear again at a randomized temporal position between 3,100 – 4,000 ms after trial onset. The visual stream containing target and distractors was identical to Experiment I. The continuous tone was also presented but did not contain rises in amplitude and therefore no task relevant event. The experimental design is illustrated in Figure 3.

As in Experiment I, 290 trials were presented and cue-target-SOA (0 vs. 100 vs. 300 ms) and number of distractors (0 vs. 1 vs. 6-8) were manipulated within subjects. The assignment of trial numbers to experimental conditions remained unchanged (see section 2.2). The first analysis step mirrored the analysis procedure applied in Experiment I (see section 2.3). Additionally, to assess a potential influence of the auditory cue feature, results of Experiments I and II were analyzed in a two-way ANOVA including the between-subject factor 'cue feature' and the within-subject factor 'number of distractors', focusing on SOA 0 ms, where the effect should be most pronounced.

Table 1

Mean target hit rates and 95% confidence intervals (CIs) in Experiments I-III

Distractors	Experiment I			Experiment II			Experiment III		
	SOA 0 ms	SOA 100 ms	SOA 300 ms	SOA 0 ms	SOA 100 ms	SOA 300 ms	SOA 0 ms	SOA 100 ms	SOA 300 ms
	<i>M</i> = 95.22	<i>M</i> = 95.87	<i>M</i> = 93.38	<i>M</i> = 94.42	<i>M</i> = 96.22	<i>M</i> = 95.05	<i>M</i> = 97.60	<i>M</i> = 97.41	<i>M</i> = 95.24
0	CI [90.60, 99.83]	CI [92.42, 99.31]	CI [87.14, 99.63]	CI [88.56, 100.27]	CI [91.76, 100.67]	CI [91.53, 98.57]	CI [95.23, 99.97]	CI [93.69, 101.13]	CI [91.32, 99.17]
	<i>M</i> = 92.42	<i>M</i> = 91.36	<i>M</i> = 92.44	<i>M</i> = 91.24	<i>M</i> = 92.51	<i>M</i> = 94.87	<i>M</i> = 95.24	<i>M</i> = 96.22	<i>M</i> = 97.11
1	CI [86.23, 98.61]	CI [84.16, 98.55]	CI [87.56, 97.31]	CI [84.56, 97.91]	CI [86.89, 98.12]	CI [90.72, 99.01]	CI [91.78, 98.71]	CI [93.68, 98.75]	CI [94.43, 99.78]
	<i>M</i> = 85.85	<i>M</i> = 88.82	<i>M</i> = 92.00	<i>M</i> = 85.79	<i>M</i> = 90.88	<i>M</i> = 90.10	<i>M</i> = 83.87	<i>M</i> = 90.76	<i>M</i> = 96.28
6-8	CI [77.65, 94.05]	CI [81.94, 95.69]	CI [86.48, 97.52]	CI [78.90, 92.69]	CI [85.29, 96.46]	CI [83.34, 96.87]	CI [75.68, 92.05]	CI [85.19, 96.33]	CI [93.29, 99.26]

### 3.2 Results

The results of Experiment II are presented in Figure 3. False alarm rates were low (multiple distractors:  $M = 2.67\%$ ,  $SD = 6.35$ ; without distractors:  $M = .89\%$ ,  $SD = 2.75$ ), and not impacted by distractor presence,  $F(1, 19) = 2.39$ ,  $p = .139$ ,  $\eta_p^2 = .112$ .

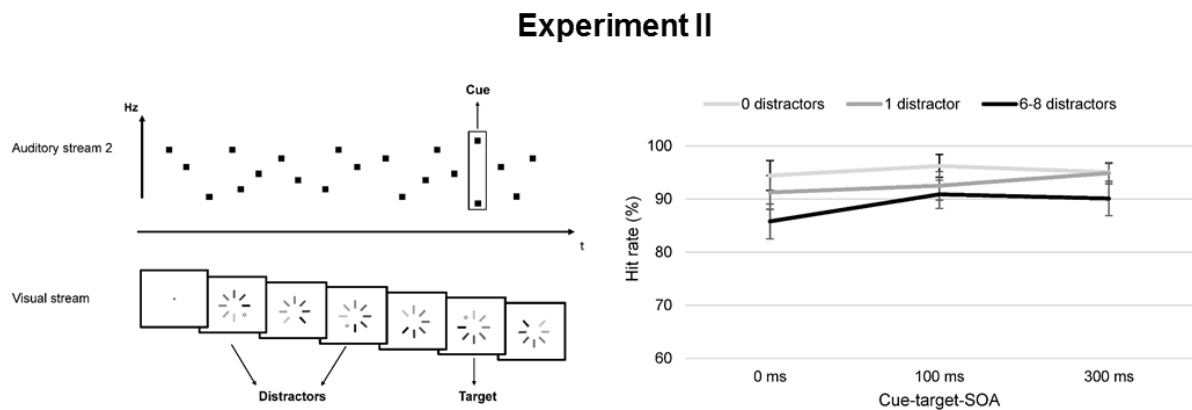
The auditory cue was detected reliably ( $M = 89.88\%$ ,  $SD = 16.48$  for multiple distractors, SOA 0 ms), and cue detection rates did not differ significantly between Experiment I and II in this critical condition,  $F(1, 37) = 2.02$ ,  $p = .169$ ,  $\eta_p^2 = .052$ . Importantly, in none of the experimental conditions including a cue significant differences in cue detection rates could be stated, indicating a comparable salience of the two cues (see Tables S1 and S2 in the Supplement).

In replication of the results of Experiment I, the number of distractors significantly influenced the detection of the subsequent target,  $F(2, 38) = 8.46$ ,  $p = .001$ ,  $\eta_p^2 = .308$ . Solely multiple distractors were associated with reduced hit rates (0 vs. multiple distractors:  $F(1, 19) = 11.26$ ,  $p = .003$ ,  $\eta_p^2 = .372$ ; 1 vs. multiple distractors:  $F(1, 19) = 8.09$ ,  $p = .010$ ,  $\eta_p^2 = .299$ ; 0 vs. 1 distractor:  $F(1, 19) = 3.19$ ,  $p = .090$ ,  $\eta_p^2 = .144$ ).

The factor 'SOA' had a significant influence,  $F(1.48, 28.27) = 4.65$ ,  $p = .027$ ,  $\eta_p^2 = .197$ , in the absence of an interaction between the SOA and number of distractors,  $F(2.31, 43.80) = .98$ ,  $p = .391$ ,  $\eta_p^2 = .049$ . Post-hoc tests between SOA conditions showed lower hit rates at SOA 0 compared to those at longer cue-target intervals (SOA 0 vs. 100 ms:  $F(1, 19) = 8.11$ ,  $p = .010$ ,  $\eta_p^2 = .299$ ; SOA 0 vs. 300 ms:  $F(1, 19) = 4.64$ ,  $p = .044$ ,  $\eta_p^2 = .196$ ). Target detection rates at SOAs 100 and 300 ms did not differ,  $F(1, 19) = .29$ ,  $p = .867$ ,  $\eta_p^2 = .002$ .

Figure 3

## Task design and results of Experiment II



*Note.* The left panel shows the task design of Experiment II: Here, the cue was a deviant tone (i.e. overlay of two pure tones) within the stream of pure tones. Target and distractors were identical to Experiment I. The right panel shows the results of the experiment: Mean hit rates (in %; y-axis) depicted for the SOA conditions (x-axis) and the number of distractors. Error bars depict standard errors of the mean. As in Experiment I, target detection rates were reduced after multiple distractor events at short cue-target-SOAs.

### Comparison between Experiment I & II: Does the auditory cue feature influence the distractor effect?

Combining the data from Experiments I and II, which solely differed in the feature defining the auditory cue, no main effect of the between-subject factor 'cue feature' could be stated,  $F(1, 36) = .23, p = .868, \eta_p^2 = .001$ . In the same way, no interaction between 'cue feature' and the within-subject factor 'number of distractors' at SOA 0 ms was observed,  $F(2, 72) = .08, p = .924, \eta_p^2 = .002$  (main effect number of distractors:  $F(1.51, 54.44) = 20.32, p < .001, \eta_p^2 = .361$ ).

### 3.3 Discussion

The influence of distractors on detection of a visual target indicated by an auditory cue observed in Experiment I was replicated in Experiment II. Additionally, Experiment II showed that the cue feature rise in amplitude could not account for the high hit rates in Experiment I since an auditory cue of constant intensity was associated with a commensurate DIB effect. Importantly, cue detection was reliable and did not differ



significantly between both experiments (see Tables S1 and S2 in the Supplement), speaking for a high and comparable salience of both auditory cues.

The presence of very similar and relatively high target hit rates in both studies is not compatible with our initial assumption that the rise in amplitude led to an especially effective orientation of attention to the target and release of the inhibition. Instead, the findings indicate that dynamics in the ‘loudness’ of an auditory cue may not systematically influence the efficiency of visual target detection during cross-modal DIB. Based on the model proposed for DIB (Niedeggen et al., 2012), the features shared between target and distractors are crucial for the effect, while the cue feature would not be expected to have a substantial influence. The cue functions as a release signal of the distractor-induced inhibitory process (Kern & Niedeggen, 2021a; Niedeggen et al., 2015) and should therefore only require a sufficient salience. The current data are in line with the assumption of the cue as a release signal.

The smaller absolute size of the cross-modal compared to the unimodal DIB was confirmed in Experiment II and could not be attributed to the auditory cue feature. However, as another alternative explanation, one could assume that the target feature local luminance change used in Experiments I and II might be a reason for the comparably weak distractor-induced effect. Maybe the local change in luminance is not associated with an efficient feature inhibition? To test this alternative explanation, in the final Experiment III, the target was now defined by a color change. This particular feature was associated with a very pronounced DIB effect within the visual modality (Winther & Niedeggen, 2017a; Winther & Niedeggen, 2018).

#### **4. EXPERIMENT III**

Cross-modal distractor-induced blindness can reliably be stated for the feature appearance of a small shape – associated with a local change in luminance –, as demonstrated by the corresponding results of Experiment I and II. Experiment III aimed to test whether the feature defining distractors and target might explain the observed high hit

rates by investigating a potential influence of the visual target feature on cross-modal DIB. So far, the brief appearance of a small white circle with black outline was used as target (and distractor) event, being embedded in a 'preloader' symbol in greyscale. This new feature should now be compared to the established feature color change, which has proven to be very efficient in eliciting feature inhibition (Winther & Niedeggen, 2017a; Winther & Niedeggen, 2018), leading to a larger DIB compared to motion stimuli. These previously observed differences, which might rely on differential processing of visual features in the cortex (i.e. ventral vs. dorsal stream) (Milner & Goodale, 2008), revealed a certain degree of feature specificity of visual DIB (Winther & Niedeggen, 2017a).

A brief color change of the preloader symbol from a default color (here: green) to a target color (here: pink) served as target event in Experiment III. If a larger cross-modal DIB effect can be observed for the feature color than for a local change in luminance, the weaker cross-modal DIB effect can be attributed to target (and distractor) feature. This would confirm the previously described feature specificity.

## **4.1 Method**

### **4.1.1 Participants**

Nineteen participants that had not participated in one of the previous two experiments took part in Experiment III. Once again, the same inclusion and exclusion criteria and required sample size as in Experiments I and II applied (section 2.1.1). Following the exclusion of one participant due to unreliable performance during pretest (criterion 1), the final sample consisted of 18 participants (13 women; 18 – 40 years of age;  $M_{age} = 27.65$ ,  $SD = 6.74$ ).

### **4.1.2 Stimuli, procedure and design**

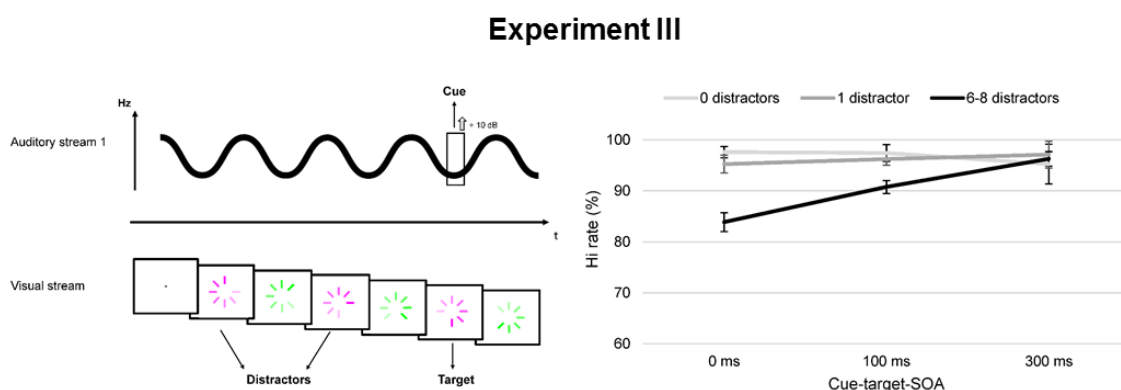
The identical stimulus material, procedure and design as in Experiment I was used, with the exception of the configuration of the visual stream. In line with the previous experiments, the visual stream consisted of a 'preloader' symbol (1.66° in diameter) with a

presentation rate of 10 Hz. The impression of a clockwise motion was once again elicited by varying the luminance of the adjacent bars. While the visual stream contained grey scales ranging from white to black in Experiments I and II, the preloader symbol could now change its color. The preloader was usually colored in green (RGB: [0 255 0]; HSV: [120 100 100]), but could change to pink (RGB: [255 0 255]; HSV: [300 100 100]) for 100 ms. Both colors were adapted from visual DIB studies (Winther & Niedeggen, 2017a; Winther & Niedeggen, 2018). Importantly, color saturation and brightness did not differ between pink and green. The luminance of adjacent bars was graded within the respective color tone to create the impression of clockwise motion. If the color change to pink occurred with or after the auditory cue, this event was the target. Color changes to pink before the cue were considered distractor events that should be ignored. As in Experiment I, the cue was defined as a short rise in amplitude in the continuous tone. Stream 2 was presented concurrently, but did not contain any task relevant stimuli. The set-up of Experiment III is depicted in Figure 4.

290 trials were presented. Once again, cue-target-SOA (0 vs. 100 vs. 300 ms) and the number of distractors (0 vs. 1 vs. 6-8) were manipulated. Trial numbers for each experimental condition and the statistical analysis performed were identical to Experiment I and II (see section 2.2). A potential influence of the between-subject factor ‘target feature’ was examined in two-way ANOVA with the within-subject factor ‘number of distractors’ and the between-subject factor ‘target feature’ for the cue-target-SOA 0 ms.

**Figure 4**

*Task design and results of Experiment III*



*Note.* The task design of Experiment III is shown in the left panel: The cue was a rise in amplitude as in Experiment I. In contrast to both previous experiments, the feature defining distractors and target was now a color change of the preloader symbol from green to pink. The right panel illustrates the results: Mean hit rates (in %; y-axis) depicted for the cue-target-SOAs (x-axis) and the number of distractors. Error bars represent standard errors of the mean. Cross-modal DIB in terms of impaired target detection at short SOAs after multiple distractors could also be stated if distractors and target were defined by a brief color change.

## 4.2 Results

The experimental results of Experiment III are displayed in Figure 4. Response behavior was again reliable and few false alarms were produced (multiple distractors:  $M = 1.93\%$ ,  $SD = 5.32$ ; without distractors:  $M = .56\%$ ,  $SD = 2.36$ ;  $F(1, 17) = 3.13$ ,  $p = .095$ ,  $\eta_p^2 = .155$ ). Cue detection rates were high ( $M = 97.64\%$ ,  $SD = 3.58$  for multiple distractors, SOA 0 ms).

In line with the previous experiments, a significant effect of the number of distractors presented before the cue could be stated,  $F(1.38, 23.48) = 9.09$ ,  $p = .003$ ,  $\eta_p^2 = .349$ . Multiple color distractors impaired target detection (0 vs. multiple distractors:  $F(1, 17) = 12.19$ ,  $p = .003$ ,  $\eta_p^2 = .418$ ; 1 vs. multiple distractors:  $F(1, 17) = 8.57$ ,  $p = .009$ ,  $\eta_p^2 = .335$ ; 0 vs. 1 distractor:  $F(1, 17) = .33$ ,  $p = .573$ ,  $\eta_p^2 = .019$ ).

Higher hit rates were observed at larger cue-target-SOAs,  $F(1.51, 25.74) = 10.21$ ,  $p = .001$ ,  $\eta_p^2 = .375$  (SOA 0 vs. 100 ms:  $F(1, 17) = 10.15$ ,  $p = .005$ ,  $\eta_p^2 = .374$ ; SOA 0 vs. SOA 300 ms:  $F(1, 17) = 12.77$ ,  $p = .002$ ,  $\eta_p^2 = .429$ ; SOA 100 vs. 300 ms:  $F(1, 17) = 3.99$ ,  $p = .062$ ,  $\eta_p^2 = .190$ ). Post-hoc tests following the significant interaction number of distractors x SOA,  $F(2.50, 42.49) = 7.08$ ,  $p = .001$ ,  $\eta_p^2 = .294$ , showed a significant distractor effect at SOAs 0 and 100 ms (SOA 0 ms:  $F(1.32, 22.38) = 11.22$ ,  $p = .001$ ,  $\eta_p^2 = .398$ ; SOA 100 ms:  $F(2, 34) = 5.11$ ,  $p = .011$ ,  $\eta_p^2 = .231$ ). At SOA 300 ms. this distractor effect had vanished ( $F(2, 34) = .83$ ,  $p = .446$ ,  $\eta_p^2 = .046$ ). In the multiple distractor condition, hit rates significantly increased with increasing cue-target-SOA,  $F(1.40, 23.86) = 13.39$ ,  $p < .001$ ,  $\eta_p^2 = .441$ , following a linear trend,  $F(1, 17) = 16.16$ ,  $p < .001$ ,  $\eta_p^2 = .487$ .

### **Comparison between Experiment I & III: Does the visual target feature influence the distractor effect?**

Experiment I and III only differed in the visual feature defining target and distractors and were compared to assess a possible influence of target feature on the cross-modal DIB effect. Importantly, the between-subject factor 'target feature' had no significant effect,  $F(1, 34) = .10, p = .753, \eta_p^2 = .003$ . No indications of feature specificity were obtained as demonstrated by the lack of a significant interaction between 'target feature' and 'number of distractors',  $F(2, 68) = 1.09, p = .342, \eta_p^2 = .031$  (main effect number of distractors:  $F(1.46, 49.54) = 22.66, p < .001, \eta_p^2 = .400$ ).

### **4.3 Discussion**

The results of Experiment III confirmed the cross-modal DIB effect with the typical behavioral characteristics for a different target feature. Importantly, a brief color change elicited a distractor effect of comparable magnitude as a change in luminance accompanying the appearance of a small white circle in Experiment I and II. The findings of Experiment III therefore contradict the notion that the overall high hit rates can be attributed to the new target feature but show that they persist for the established feature color change. In contrast to the unimodal DIB, we found no indications for a feature specificity of the cross-modal effect. Consequently, the finding of a relatively small cross-modal distractor effect elicited by a feature that was associated with a large "blindness" in the visual modality (Winther & Niedeggen, 2018) speaks for substantial differences between target detection in purely visual and cross-modal settings. These differences appear to be linked to the modality the cue is presented in: an auditory cue presumably supports visual target detection at short cue-target-SOAs more efficiently than a visual cue.

In sum, the observation of a highly significant, but comparably small decrease in target detection in the multiple distractor condition in all experiments indicates that despite the distractor-driven inhibitory process, visual target detection appears to succeed more often in cross- than in unimodal conditions.

## 5. General Discussion

### 5.1 Summary of results

In three behavioral experiments, a consistent effect of multiple visual distractors on the detection of a visual target, which was indicated by an auditory cue, was found. Confirming cross-modal distractor-induced blindness, target detection was most affected if cue and target appeared simultaneously and the transient “blindness” had mostly vanished at a cue-target-SOA of 300 ms. Furthermore, it was demonstrated that the appearance of a small circle, associated with a local change in luminance, also elicits the inhibitory process underlying DIB, establishing a new visual feature. However, the cross-modal distractor effect was smaller than previously observed within the visual modality, as well as for auditory target detection in unimodal and cross-modal conditions. The expression of the cross-modal DIB did neither depend on the feature of the auditory cue (increase in amplitude vs. frequency composition), nor on the feature of the visual target (local luminance change vs. color change). Implications of the experimental results will be discussed in the following.

### 5.2 Implications for the inhibitory model underlying distractor-induced blindness

Multiple distractors, sharing the features of a target event, hinder target detection in the visual (Michael et al., 2011; Sahraie et al., 2001) and auditory modality (Kern & Niedeggen, 2021a), as well as in cross-modal conditions with cue and target stemming from different sensory modalities (Kern & Niedeggen, 2021b). The current data provide reliable evidence that in line with the hypothesis, this distractor effect can also be observed if an auditory cue indicates the appearance of a visual target. Consequently, for all four possible combinations of cue and target within vision and audition, an effect of distractors on target perception can be stated. Independent of the characteristics of cue and target, it was consistently observed that (1) multiple distractors are required to decrease hit rates, while one distractor is not sufficient, and (2) that the largest distractor effect occurs at a cue-target-SOA of 0 ms and decreases with increasing temporal distance between cue and target.

Experiments I and II confirmed a new visual feature, the appearance of a small circle, associated with a local change in luminance, for the DIB effect, therefore extending previous findings on distractor effects for motion, orientation and color (Michael et al., 2011; Winther & Niedeggen, 2018). That the distractor effect can be elicited by a variety of features, provided they are shared between distractors and target, indicates a large amount of feature adaptability for DIB.

In sum, these findings are in line with the assumption that DIB is caused by the cumulative activation of a negative attentional set by the repeated presentation of task-irrelevant, but target-like stimuli (Hesselmann et al., 2006; Niedeggen et al., 2012). Consequently, the same inhibitory mechanism seems to apply within visual and auditory modality, as well as in both possible combinations of these modalities.

However, the current findings also provide extensions of the DIB model. While cue salience can influence the expression of the distractor effect (Hay et al., 2006), Experiments I and II gave first evidence that the (auditory) cue feature does not seem to impact the efficiency of the distractor-induced inhibition when perceptual load and salience are kept constant. The cue appears to function as a signal for the deactivation of the distractor template, which requires a sufficient salience of the cue but apparently no specific auditory feature. This indicates in combination with previous results that the occurrence of the distractor effect is neither dependent on cue and target occurring in the same modality (Kern & Niedeggen, 2021b), nor on the feature defining the cue. It remains to be examined whether comparable distractor effects for different cue features can also be observed in unimodal settings (e.g., visual), which would be expected based on the DIB model.

Another addition to the model lies in potential differences in the feature specificity of the effect between uni- and cross-modal DIB. For the visual modality, larger inhibitory effects for the target/distractor feature color than for motion stimuli were found, indicating some amount of feature specificity of inhibitory processes (Ariga & Kawahara, 2004; Winther & Niedeggen, 2017a; Winther & Niedeggen, 2018). In contrast, for cross-modal DIB, the

current data revealed that a color change is apparently as efficient as a local change in luminance in eliciting a target detection deficit. Whether different visual features are associated with inhibitory effects of different sizes might rely on the modality the cue is presented in. During unimodal DIB, a visual dual task, associated with high perceptual load in the visual modality, is presented. During cross-modal DIB, the dual task consists of one visual and one task-relevant auditory stream, which could be linked to a lower perceptual load and more available resources within each modality (Arrighi et al., 2011; Keitel et al., 2013). Consequently, it could be very cautiously proposed that feature specific effects regarding the inhibitory process might only be observable under high load conditions, and do therefore not occur in cross-modal tasks. Alternatively, instead of differences between unimodal and cross-modal processing, the observed lack of feature specificity for cross-modal DIB might be attributed to a similar functioning of feature inhibition for all properties that are processed in the same visual pathway. A color change and the appearance of a small circle are both features that are predominantly processed in the ventral visual stream (Kravitz et al., 2013). However, differences in inhibitory processes between predominantly 'ventral' and 'dorsal' features, as observed for visual DIB (Winther & Niedeggen, 2018), may exist, while taking into account that both pathways are interconnected (Goodale & Milner, 2010; Kravitz et al., 2013; Schenk & McIntosh, 2010). Both preliminary explanations require examination in future studies to pinpoint which account is more fitting.

## **5.2 Modality-specific differences in the magnitude of the distractor effect**

Crucially, the current data allow a comparison of the magnitude of distractor-induced blindness and deafness in uni- and cross-modal conditions. In the visual domain, distractor effects on hit rate (here defined as: zero distractor – multiple distractor condition at cue-target-SOA 0 ms) are very pronounced (i.e. 30 % for orientation stimuli (Niedeggen et al., 2012); 46% for color stimuli (Winther & Niedeggen, 2017a); 27% for motion stimuli (Michael et al., 2011)). In comparison to the visual effect, distractor-induced deafness shows a smaller magnitude. Unimodal and cross-modal DID appear to be roughly comparable in size



(unimodal: 8-23% (Kern & Niedeggen, 2021a); cross-modal: 13-28% (Kern & Niedeggen, 2021b)). The current findings in a cross-modal set-up with an auditory cue and a visual target suggest that under these circumstances, the distractor-induced target detection deficit is the smallest (i.e. 9-14%).

The observation of modality-specific differences in the size of the distractor effect raises the question how these differences can be accounted for. First, the high hit rates in the current study might be attributed to a response bias. This explanation can be ruled out, as in all three experiments, the number of false alarms was low (i.e., 0.6 – 3.5 %), indicating reliable response behavior. Second, it could be assumed that fundamental differences in the processing of distractors between visual and auditory modality exist (e.g., (Lavie & Tsai, 1994; Murphy et al., 2013), leading to larger distractor effects in visual compared to auditory modality. However, the data acquired with the DIB/DID paradigm are not in line with this assumption. A third possible explanation concerns the cue: the distractor effect might be more pronounced if the release signal is visual compared to auditory. Strikingly, the previous and current data provide some preliminary evidence for a possible impact of the modality the cue is presented in. The numerically smallest DIB/DID effects were observed if the cue stemmed from the auditory modality. This could indicate that an auditory cue might be an especially effective release signal, possibly due to the function of the auditory modality as 'early warning system' (Dalton & Lavie, 2007). However, the modality of the cue cannot provide a stand-alone explanation since unimodal DID appears to be more pronounced than cross-modal DIB, even though an auditory cue was present both times. Therefore, not only the modality the cue is presented in might have an impact but also if the task involves uni- or cross-modal stimulation.

Notably, reduced effects in cross-modal as compared to unimodal tasks have been reported for the related phenomena attentional blink (Arnell & Jenkins, 2004) and inattention blindness (Sinnott et al., 2006). Arnell and Jenkins (2004) stated that the visual attentional blink appears to be larger than the auditory effect, while cross-modal target

detection deficits are usually the smallest (and are often not found at all, see (Hein et al., 2006; Soto-Faraco & Spence, 2002; Van der Burg et al., 2007)). Strikingly, Arnell and Jenkins (2004) observed that the cross-modal AB at short lags was smaller if a visual second target (T2) followed an auditory first target (T1) than vice versa. In contrast to the typical visual blink and the cross-modal effect for reversed modalities, visual T2 detection after an auditory T1 was enhanced at short compared to long T1-T2-intervals. This was interpreted as an auditory cueing effect exclusively occurring in this cross-modal condition (Arnell & Jenkins, 2004). This previous finding is in line with our current results and with the assumption that visual target detection succeeds more often, if an auditory compared to a visual cue precedes or accompanies the target. During DIB, an auditory cue seems to enable a faster and more efficient allocation of attention to the visual target and a faster release of the negative attentional set than a visual cue stemming from the same sensory modality than the target.

Multisensory research has established that a sound often enhances detection of a visual target, if they occur in temporal proximity (Chang et al., 2015; Fiebelkorn et al., 2011; Frassinetti et al., 2002; Koelewijn et al., 2010; Kusnir et al., 2011; Noesselt et al., 2010; Petersen et al., 2017; Van der Burg et al., 2008). These multisensory enhancement effects have been linked to the integration of temporally overlapping visual and auditory signals into one percept (Koelewijn et al., 2010; Senkowski et al., 2007; Wallace et al., 2020), to a cross-modal spread of attention (Talsma et al., 2010; Tang et al., 2016), and to auditory alerting (Kusnir et al., 2011). Multisensory enhancement effects could provide one suitable explanation for the relatively small cross-modal DIB effect observed here. An attentional enhancement of visual target processing caused by the auditory cue might have counteracted the distractor-driven inhibition of attentional allocation to target features to some degree. Therefore, the distractor effect might have been reduced at short cue-target-SOAs compared to unimodal settings.

Taken together, modality-specific differences in the magnitude of the distractor-induced decrease in hit rates can preliminarily be stated. These differences might be attributed to the modality the cue occurs in, with an auditory cue possibly acting as an especially effective release signal of the negative attentional set, and to particularities of cross-modal processing.

### **5.3 Limitations**

One limitation of this study is that the present data do not enable a definite answer to the question as to why cross-modal DIB is a reliable, but smaller effect than observed in previous studies. Future research should aim to clarify whether the current findings are due to an auditory enhancement of visual processing, leading to increased hit rates at short cue-target-intervals and an especially efficient release of the negative attentional set, or if alternative explanations are more suitable. Furthermore, it remains unclear, why a visual cue did not lead to an enhancement of auditory target detection compared to unimodal DID (Kern & Niedeggen, 2021a, 2021b), speaking for some specificity of multisensory enhancement regarding the modalities cue and target are presented in. It has been reported that a task-irrelevant light can improve auditory perception in contrast to the absence of a visual signal (Lovelace et al., 2003; Odgaard et al., 2004). However, our previous results indicated that a task-relevant visual cue embedded in a RSVP stream does not improve auditory detection in comparison to the unimodal setting (Kern & Niedeggen, 2021a, 2021b). Future studies should examine the modality-specific differences in DIB/DID in more detail to not only improve insight in possible differences in cue and target processing between sensory modalities but also in distinctions between cross-modal settings.

### **5.4 Conclusion**

In sum, it was demonstrated that an inhibitory effect of visual target-like distractors on visual target detection can be stated if the signal for task relevance stems from the auditory modality. The observed cross-modal distractor-induced blindness was reduced in size compared to the cross-modal effect for reversed modalities as well as the unimodal

distractor-induced blindness but exhibited the same characteristics. Since neither cue nor target feature could account for the smaller cross-modal blindness, our results indicate that an auditory cue provides an especially efficient release signal of the inhibited visual features. Compared to a visual signal of task relevance, an auditory cue might lead to a faster attentional allocation to the target stream, especially in cross-modal conditions, where multisensory enhancement effects might boost target detection.

## Supplementary material Study III

## Supplement 1: Cue detection in Experiment I and II

Table S1

Cue detection rates in Experiment I and II

Distractors	Experiment I			Experiment II		
	SOA 0 ms	SOA 100 ms	SOA 300 ms	SOA 0 ms	SOA 100 ms	SOA 300 ms
0	$M = 95.83$ CI [90.79, 100.87]	$M = 93.61$ CI [87.73, 99.49]	$M = 93.33$ CI [88.32, 98.79]	$M = 94.28$ CI [89.62, 98.95]	$M = 91.67$ CI [86.22, 97.11]	$M = 92.14$ CI [87.50, 96.79]
1	$M = 93.89$ CI [88.83, 98.95]	$M = 92.50$ CI [85.78, 99.22]	$M = 93.33$ CI [87.24, 99.42]	$M = 91.91$ CI [87.22, 96.59]	$M = 91.67$ CI [85.44, 97.89]	$M = 93.33$ CI [87.69, 98.97]
6-8	$M = 95.69$ CI [89.61, 101.78]	$M = 93.89$ CI [88.98, 98.79]	$M = 92.64$ CI [86.95, 98.37]	$M = 89.88$ CI [84.25, 95.51]	$M = 89.88$ CI [85.34, 94.43]	$M = 90.12$ CI [84.85, 95.39]

*Note.* Experiment I included a transient rise in amplitude in a continuous tone as cue, while in Experiment II the cue was defined as a deviance in frequency composition in a sequence of sine-wave tones. Mean cue detection rates and 95% confidence intervals (CIs) are provided for each experimental condition containing a cue.

Table S2

*Statistical comparison of cue detection rates between Experiment I and II for all experimental conditions including a cue*

	Experiment I vs. Experiment II
SOA 0, 0 distr.	$F(1, 37) = .21, p = .651, \eta = .006$
SOA 0, 1 distr.	$F(1, 37) = .34, p = .563, \eta = .009$
SOA 0, 6-8 distr.	$F(1, 37) = 2.02, p = .164, \eta = .052$
SOA 100, 0 distr.	$F(1, 37) = .24, p = .626, \eta = .006$
SOA 100, 1 distr.	$F(1, 37) = .03, p = .855, \eta = .001$
SOA 100, 6-8 distr.	$F(1, 37) = 1.47, p = .232, \eta = .038$
SOA 300, 0 distr.	$F(1, 37) = .13, p = .726, \eta = .003$
SOA 300, 1 distr.	$F(1, 37) = .00, p = 1.000, \eta = .000$
SOA 300, 6-8 distr.	$F(1, 37) = .43, p = .514, \eta = .012$
Cue, no target, 0 distr.	$F(1, 37) = .06, p = .800, \eta = .002$
Cue, no target, 6-8 distr.	$F(1, 37) = .52, p = .474, \eta = .014$

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## CHAPTER 6

### General discussion

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This dissertation aimed to examine distractor-induced blindness outside of the visual modality for the first time by adapting the paradigm to auditory and cross-modal settings. Additionally, this thesis aimed to assess electrophysiological NCCs of auditory awareness within these settings. The empirical findings reported in Chapters 3 – 5 are summarized in the following section 1. Consecutively, implications and scientific contributions of the behavioral and electrophysiological results are discussed (section 2) and limitations are considered (section 3). Various future research perspectives are proposed based on the discussion of results. This final chapter closes with a brief conclusion (section 4).

### 1. Summary and interpretation of the findings

*Study I: Can a distractor-induced deafness with the typical characteristics of DIB be found within the auditory modality? What are electrophysiological signatures of successful auditory target detection?*

In Study I, the DIB paradigm was adapted to the auditory modality to examine the existence of a *distractor-induced deafness* (DID) and to investigate electrophysiological signatures of auditory target awareness. Behavioral data revealed that a distractor-induced deafness can indeed be stated: multiple target-like distractors impaired access to an auditory target. This effect was as expected most pronounced at a cue-target-SOA of 0 ms. The presentation mode of the auditory stimuli (separate vs. superimposed streams) had no significant effect. In the following - and analogous to the original DIB task - , the DID paradigm incorporated two spatially separate auditory streams. This study provided a first and successful adaption of the DIB paradigm to the auditory modality and demonstrated that the inhibitory effect of multiple distractors on target detection can also be found for auditory stimuli.

In addition to the behavioral findings, ERP signatures of auditory awareness were assessed. Processing of detected auditory targets showed two differences in ERPs compared to missed targets. As hypothesized and in line with previous visual findings

(Niedeggen et al., 2015; Niedeggen et al., 2002), hits showed a larger posterior P3 component than misses. This late correlate may represent post-perceptual updating of the target into working memory, associated with inter-areal communication processes (Soto & Silvanto, 2014). Furthermore, this finding is in line with 'late' theories of consciousness like the GNWT. The GNTW suggests that the P3 depicts the activation of a broad fronto-parietal network and therefore the process underlying access consciousness (Dehaene et al., 2011). Additionally, hits also elicited an enhanced frontal negativity (FN) around 200 ms after target onset, preceding the P3. This is in contrast to visual DIB studies where solely a P3 difference was found. We linked this early correlate to the recovery of attentional control, as depicted by the frontal component of a processing negativity (Näätänen et al., 2011), associated with the release of the distractor-induced inhibition. This (re-)activation of attentional control might enable allocation of selective attention to the target and thus increase chances of conscious access. In sum, the ERP results of Study I indicated that an early as well as a late, high-level process contribute to conscious auditory perception.

*Study II: Is the distractor effect on target detection also observable if the cue is visual and the target auditory? Can the electrophysiological correlates of auditory target access observed in Study I be replicated in this cross-modal setting?*

In Study II, distractor-induced deafness was examined in a cross-modal, auditory-visual setting with the cue now being a visual stimulus. In line with the first hypothesis, multiple distractors were associated with a significant impairment of auditory target detection under cross-modal stimulation. This cross-modal DID was most expressed at short cue-target-SOAs. The release of the distractor-driven inhibition apparently takes more time under these stimulus conditions: a significant distractor effect persevered at a SOA of 300 ms. The behavioral results demonstrated that distractor-induced deafness persists if cue and target occur in different sensory modalities. Therefore, the findings extend the model behind DIB.

The replicability of the electrophysiological findings of Study I in a multisensory setting was tested by once again assessing ERP correlates of auditory awareness using the



contrastive approach. Importantly, the early frontal signature of auditory awareness was successfully replicated: using identical electrode clusters, a larger anterior negativity for detected targets was found in the same 180 – 240 ms time window. This finding strengthens the notion of a reliable, early correlate of auditory target access. In contradiction to the hypothesis and to unimodal findings acquired with the DIB/DID paradigm, we observed no difference in a late P3. This result is not in line with the assumption of the P3 as a universal signature of consciousness. In addition to the frontal negativity, hits and misses also differed in a sustained negativity (SN) in succession to the FN, which showed a global, widespread topography. This preliminary finding might depict a cross-modal spread of attention associated with multisensory integration (Busse et al., 2005; Talsma et al., 2010). Consequently, conscious processing during cross-modal DID appears to be finished preceding the late positive component and after completion of the processes underlying FN and SN.

A post-hoc correlation analysis showed that the P3 amplitude, but not FN and SN, was linked to the individual target discrimination ability  $d'$ . In the same way, high performing participants (<10 misses in the multiple distractor condition; “distractor-insensitive” subgroup) showed a larger P3 effect ( $P3_{hit} - P3_{cue\ only}$ ) compared to “distractor-sensitive” participants. Both subgroups did not differ regarding FN and SN effects. These additional analyses in combination with no indications of a P3 difference between hits and misses suggest that the P3 depicts decision processes such as decision certainty during cross-modal DID and not conscious access.

*Study III: Can distractor-induced blindness be found if the cue is auditory and the target visual? Is the distractor effect influenced by the feature defining the auditory cue? Does the visual target feature influence the cross-modal effect?*

In Study III, we examined a distractor effect on target detection in cross-modal conditions with reversed modalities compared to Study II (i.e., auditory cue, visual target). Additionally, potential influences of different cue and target features on cross-modal DIB

were examined. As hypothesized, distractor-induced blindness was observed in this cross-modal setting, exhibiting the typical behavioral characteristics: multiple distractors impaired target detection and the largest decrease in hit rates occurred if cue and target appeared simultaneously. Likewise visual DIB (Sahraie et al., 2001; Winther & Niedeggen, 2017b), target detection had recovered at a cue-target SOA of 300 ms. Therefore, cross-modal DIB could be confirmed.

Importantly, the substantial distractor effect consistently found in all three behavioral experiments was smaller than previously observed within the visual modality. In a direct comparison with the behavioral experiment of Study II, it was revealed that the target detection deficit was more pronounced during cross-modal DID than during cross-modal DIB. Thus, distractors apparently have a smaller impact on target detection if the cue is auditory and the target visual than vice versa.

The finding of a reduced cross-modal DIB could be explained neither by the physical feature defining the cue nor by the target feature. We obtained comparable results for a rise in amplitude and a deviance in frequency composition as cues, which both did not differ in salience. An increase in loudness was therefore equally efficient in redirecting attention to the target as a change in frequency composition. With reference to the third research question, the new feature “appearance of a small circle”, associated with a local change in luminance, was compared to the established feature color change to examine whether the reduced DIB could be attributed to this new feature. A color change had shown a high efficiency in eliciting the inhibitory process in vision (Winther & Niedeggen, 2018). The data showed that the two different visual features defining target and distractors were associated with a comparable distractor effect. Therefore, for these two features, a similar strength of the distractor-driven inhibitory process was observed and no indications for a feature specificity of the distractor-induced inhibition were obtained for cross-modal DIB. The reduced magnitude of DIB under cross-modal compared to unimodal conditions or to cross-modal DID may be attributed to two processes. First, the auditory cue might act as an

especially efficient release signal of the negative attentional set. Second, the auditory signal might have enhanced visual target processing if cue and target appear in temporal proximity (Koelewijn et al., 2010; Noesselt et al., 2010; Petersen et al., 2017). This multisensory enhancement induced by the auditory cue could have counteracted the distractor-induced inhibition of the visual target features to some degree.

## **2. Implications and scientific contribution of the findings**

### **2.1 Implications for the model behind distractor-induced blindness**

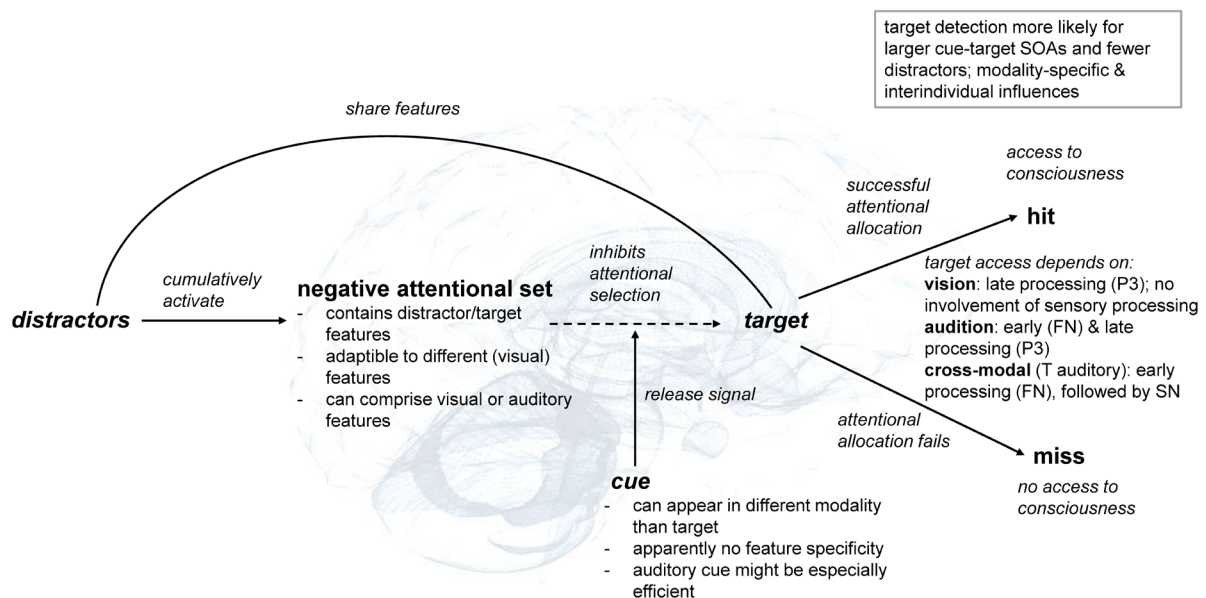
The first main aim of this thesis was to experimentally validate an adaption of the DIB paradigm to auditory and cross-modal settings. Studies I-III revealed that multiple, target-like distractors led to a decrease in target detection in auditory and auditory-visual stimulus conditions. Therefore, they provided a successful validation of the adapted paradigms. Additionally, the findings are first evidence for the transferability of the DIB effect to different sensory modalities. Table 1 gives an overview of experimental findings and open research questions regarding the DIB/DID paradigm in visual, auditory and cross-modal settings.

The experimental findings of all studies incorporated in this dissertation generally support the model proposed for DIB (Hesselmann et al., 2009; Hesselmann et al., 2006; Michael et al., 2011; Niedeggen et al., 2015; Niedeggen et al., 2012). Furthermore, they show that it can be expanded to auditory and cross-modal settings. The model suggests that multiple distractors cumulatively activate a negative attentional set. According to the theoretical model, the cue announces that the target can now occur and therefore signals a release of the inhibitory attentional set. However, this deactivation does not happen immediately, leading to impaired target detection at short cue-target-SOAs since attention is still directed away from target features. In line with this, in all modality combinations investigated so far, target hit rates deteriorated the most if cue and target appeared simultaneously and recovered with increasing cue-target-SOA. The studies comprised in this thesis extend previous research by providing evidence that the DIB model applies not only to

visual but also to (simple) auditory stimuli, as well as to auditory-visual stimulus conditions. The finding of a distractor-induced deafness speaks for top-down feature inhibition working in a similar manner in the auditory modality than in vision (Dalton & Lavie, 2007; Joos et al., 2014). Figure 1 displays an illustration of the updated and extended model for DIB/DID and incorporates the findings of Studies I-III. The investigation of distractor effects in other modalities than the visual and auditory one, as well as in cross-modal settings between these different modalities could be an interesting avenue for future research. Studies like these could determine whether DIB is a phenomenon shared between all sensory modalities.

**Figure 1**

*Updated and extended model for distractor-induced blindness/deafness*



Previous research found that the distractor-driven inhibitory process can be activated for the three different visual features orientation, motion, and color (Michael et al., 2011; Winther & Niedeggen, 2017a). In Study III, we demonstrated that the appearance of a small white circle with black outline, associated with a local change in luminance, is a fourth feature that can elicit DIB. Consequently, it can be stated that the inhibitory process underlying DIB shows an adaptability across different visual feature dimensions, which is in accordance with assumptions of the boost and bounce theory (Olivers & Meeter, 2008). Additionally, DIB can

be elicited by features predominantly processed in ventral pathways (i.e., color, appearance of small circle), as well as by features primarily processed in the dorsal visual stream (i.e., orientation, motion). In summary, it can be stated that DIB can be evoked by a variety of different (visual) features - provided this feature is shared between distractors and target (Michael et al., 2012; Winther & Niedeggen, 2017a). This demonstrates the generality of the visual effect. Future research could investigate the feature adaptability of the inhibitory process outside of the visual modality. If DID can be observed for different auditory features, as would be expected, this speaks for the notion that feature inhibition via negative attentional sets works in a similar fashion for different sensory features within different sensory modalities. Furthermore, future studies could use more complex and naturalistic stimuli, such as faces or natural speech. The observation of DIB/DID for such a new class of complex stimuli would further support the feature adaptability and the universal validity of the behavioral phenomenon.

Further expansions of the DIB model that were provided by the current findings concern the role of the cue. Importantly, Studies II and III demonstrated that the distractor effect can also occur if the cue is presented in a different sensory modality than the target. In contrast to related phenomena like the attentional blink, for which cross-modal findings have been heterogeneous (Arnell, 2006; Finoia et al., 2015; Van der Burg et al., 2007), the current results demonstrate that DIB/DID can be consistently observed if cue and target stem from different modalities. Furthermore, two different auditory cue features with similar salience were associated with a comparable distractor effect in Study III, suggesting a lack of feature specificity for the (auditory) cue. Both observations are in line with the assumption of the cue working as a release signal of the negative attentional set. A release signal would require a sufficient salience, which was given in all studies, as demonstrated by an unproblematic detection of the cue (i.e., 88 - 98% cue detection at SOA 0 ms in Studies I - III). Apparently, the release of the inhibition works regardless of cue and target appearing in the same or different modalities, the spatial proximity between both stimuli (Hesselmann et al., 2009) and the features defining the cue. However, the efficiency of the release signal seems to depend

on the modality the cue is presented in: the smallest distractor effects occurred in settings with an auditory cue (see Table 1). An auditory compared to a visual cue might be a more efficient release signal of the feature inhibition, possibly leading to a faster (re-)allocation of attention to the target stream. The higher efficiency of auditory cues might be attributed to the function of the auditory modality as an early warning system (Dalton & Spence, 2007). Future studies should follow up on the observations regarding a potential effect of modality and the lack of feature specificity for the (auditory) cue.

Taken together, the behavioral findings comprised in this dissertation show that distractors can make not only “blind” but also “deaf” regarding the detection of a relevant stimulus. This influence of distractors can be stated in unimodal as well as in cross-modal conditions. The transferability of distractor-induced blindness to settings outside of the visual modality was therefore demonstrated. Consequently, a general inhibitory mechanism that applies across sensory modalities can be assumed.

## **2.2 Electrophysiological correlates of auditory awareness**

The second main aim of this dissertation was to examine ERP correlates of auditory target access. Studies I and II consistently found a relatively early ERP component being linked to target awareness: a frontal negativity occurring about 200 ms after cue/target onset showed an enhanced amplitude for hits. Thus, the results speak for a reliable association between this frontal process and auditory consciousness. Congruent with the finding of the FN, other recent studies using different experimental paradigms also reported an early frontal correlate of auditory awareness with similar topography and latency (Eklund et al., 2021; Eklund & Wiens, 2019; Schlossmacher et al., 2021). This early signature was proposed as ‘auditory awareness negativity’ (AAN). A consistent link between an early ERP correlate and auditory target detection supports ‘early’ models of awareness, which suggest a crucial role of sensory processing for conscious perception, such as the recurrent processing theory (Lamme, 2006).

**Table 1**

Overview of experimental findings with the DIB/DID paradigm in different modalities and of open research questions

	visual	auditory (Study 1)	cross-modal (target auditory) (Study 2)	cross-modal (target visual) (Study 3)
<b>target features examined</b>	motion, orientation, color	rise in amplitude	rise in amplitude	appearance of a small white circle, color
<b>cue features examined</b>	color, letters (Hay et al., 2006), white dots (Winther & Niedeggen, 2017a; 2018)	deviance in frequency composition	appearance of small white circle	rise in amplitude, deviance in frequency composition
<b>multiple distractors impair target detection?</b>	✓	✓	✓	✓
<b>cumulative distractor effect?</b>	✓	✓	?	?
<b>effect of cue-target SOA?</b>	✓	✓	✓	✓
<b>feature specificity?</b>	✓	?	?	?
<b>feature adaptability?</b>	✓	?	?	✓
<b>different efficiency of target features?</b>	color > motion (Winther & Niedeggen, 2018)	?	?	no?
<b>size of distractor effect (0 - multiple distr., SOA 0 ms)</b>	46% for color change (Winther & Niedeggen, 2017a); 30% for orientation (Niedeggen et al., 2012)	8-23%	13-28%	9-14%
<b>false alarm rates (with distractors)</b>	4-8% (Winther & Niedeggen, 2018), 14% (Niedeggen et al., 2012)	17-34%	19-26%	2-3%
<b>distractor-evoked ERPs</b>	frontal negativity, linked to misses (Niedeggen et al., 2015)	?	?	?
<b>ERP correlates of target detection</b>	late centro-parietal P3 (600 - 800 ms); no early correlate (Niedeggen et al., 2015)	early frontal negativity (180 - 240 ms) & late centro-parietal P3 (540 - 600 ms)	early frontal negativity (180 - 240 ms) & sustained negativity (240 - 480 ms); no difference in P3	?

However, while the observed early frontal negativity may reflect an AAN, originating in auditory cortices (Dembski et al., 2021; Wiegand & Gutschalk, 2012), the processes underlying this component are not completely clear. Most importantly, the relation between this early component and selective attention remains uncertain. The AAN shows many similarities with established attention-related negativities occurring in the same time window, showing a similar topography and often also a contralateral maximum (i.e., selection negativity, N2pc, frontal processing negativity) (Bola & Doradzińska, 2021). In Study I, we proposed that the FN may depict the frontal component of a processing negativity linked to the (re-)activation of top-down attentional control (Näätänen et al., 2011). This reactivation of attentional control could enable the allocation of attention to the target. Future research needs to determine whether the early correlate of auditory awareness depicts an attentional process necessary for awareness, and therefore a prerequisite, or a sensory correlate of awareness (see (Aru et al., 2012) for a proposed taxonomy). Since selective attention is often regarded as a process necessary for awareness to arise (Cohen & Chun, 2017; Dehaene et al., 2006; Jensen et al., 2011; Pitts et al., 2018), early NCCs may always be confounded with, or least strongly influenced by, attentional processes.

In addition to the early frontal negativity, in the cross-modal Study II a sustained negativity succeeded the FN, which also showed a larger amplitude for hits. This sustained negativity persisted for several hundred milliseconds and exhibited a widespread topography over frontal, central, and posterior electrodes. In visual and auditory settings, no similar correlate has been observed. The sustained negativity might therefore constitute a cross-modal signature of (auditory) awareness. It could depict a cross-modal spread of attention necessary for the integration of information from different modalities (Busse et al., 2005; Talsma et al., 2010). While this finding requires replication, it remains unclear whether a similar ERP signature can be observed for visual target detection during cross-modal DIB, or if the sustained negativity is specific to the processing of an auditory target in a cross-modal environment. A cross-modal ERP study investigating correlates of visual target access,



which is currently in preparation, will help to explore the replicability and specificity of the sustained negativity.

The P3, which has been proposed as a late signature of awareness (Boncompagni & Cosmelli, 2018; Dehaene et al., 2011; Naccache et al., 2016; Salti et al., 2012; Sergent et al., 2005), only showed an enhanced amplitude for hits in Study I but not in Study II. The lack of the hypothesized P3 effect during cross-modal DID does not support the notion of the P3 as a reliable, universal correlate of awareness. In this cross-modal task, cortical processing necessary for target access was apparently already completed before the onset of the late positive component. It has been put forward that instead of conscious access, the P3 may reflect post-perceptual processes subsequent to awareness, such as response requirements (Cohen et al., 2020; Mazzi et al., 2020; Pitts et al., 2014; Schröder et al., 2021; Verleger, 2020; Whyte et al., 2021) and decision making (Koivisto et al., 2016; Twomey et al., 2015). Recently, Sergent et al. (2021) suggested that the P3 depicts decision processes in active auditory tasks requiring report. If no decision regarding stimulus detection is required, conscious access might arise in the absence of a P3 (Sergent et al., 2021). The authors concluded that while the P3 is not a correlate of conscious access per se, it reflects decision processes which are closely linked to conscious access (Sergent et al., 2021). The observed correlation between target discrimination ability  $d'$  and P3 effect in Study II, as well as the enlarged P3 for hits for high-performing “distractor-insensitive” compared to “distractor-sensitive” individuals are in line with the assumption of the P3 as a reflection of decision processes. In this cross-modal setting, the P3 might indicate decision certainty and task performance instead of awareness. Consequently and in contradiction to the GNWT (Dehaene et al., 2011), the P3 may – at least in some settings – represent a consequence of awareness, and not a correlate of consciousness. In the same way, recent functional magnetic resonance imaging (fMRI) studies indicated that activity in the fronto-parietal network does not show the often-reported correlation with conscious access (Dehaene et al., 2001; Haynes et al., 2005; Marois et al., 2004), if responses are controlled for ((Farooqui & Manly, 2018; Frässle et al., 2014; Schröder et al., 2019), but see (Whyte et al., 2021)). Study

II indicated that a P3 effect can be absent even if the task requires report, which has also been observed for somatosensory stimuli (Schröder et al., 2021). In summary, there is not yet a final answer to the question which processes this famous ERP component depicts in the context of consciousness research (Mashour et al., 2020). Evidence is accumulating that the P3 might sometimes depict a consequence and not a 'true' signature of awareness.

The ERP findings incorporated in this dissertation provide a contribution to the search for auditory NCCs. It is of scientific importance to assess and compare NCCs in different modalities to examine the generality of candidate NCCs (Sergent et al., 2021) and the existence of modality-specific differences. When comparing the results of Studies I and II with previous visual findings, a different picture can be stated for visual and auditory target processing. For visual DIB, solely a late positivity showed an enhancement for hits in the absence of an early correlate (Niedeggen et al., 2015; Niedeggen et al., 2002). These results appear to be contradictory to Study II, where auditory awareness was exclusively linked to processes preceding the P3. In contrast to visual awareness during DIB, auditory target awareness seems to depend on an early frontal process, succeeded by a late positivity in unimodal and a sustained negativity in cross-modal conditions. It can therefore be assumed that fundamental differences in the neural processing underlying access to awareness during DIB/DID may exist between sensory modalities. Access to visual and auditory targets during DIB/DID appears to involve – at least partly – different processes and might follow a different time course.

However, an early signature of awareness has not only been observed in the auditory domain but also in the visual (Förster et al., 2020; Koivisto et al., 2016; Pitts et al., 2014; Rutiku et al., 2015; Schlossmacher et al., 2020), and somatosensory modality (Schröder et al., 2021). According to Dembski et al. (2021), a 'perceptual awareness negativity' (PAN) arising after around 200 ms might be a 'true NCC' that can be found across sensory modalities and originates in the respective sensory cortices. While some visual studies, like the DIB studies, only found a P3 effect (Babiloni et al., 2005; Turatto, Angrilli, et al., 2002),

many others reported an early posterior signature of visual awareness (visual awareness negativity; VAN). Sometimes this early correlate occurred in combination with a succeeding P3 (Filimonov et al., 2022; Zivony & Lamy, 2021), and sometimes as the only reliable correlate (Förster et al., 2020; Schelonka et al., 2017; Schlossmacher et al., 2020).

Whether an early ERP marker of visual awareness can be observed might, possibly among other factors, depend on the task design and stimulus material. Visual DIB studies contrasting hits and misses used dynamic target/distractor features predominantly processed in the dorsal visual stream (i.e., orientation, motion) (Kravitz et al., 2013). In contrast, the majority of visual studies applies static features associated with ventral stream processing (Boncompagni & Cosmelli, 2018). Boncompagni and Cosmelli (2018) also observed a P3 effect for local motion stimuli, in the reported absence of a VAN. However, the authors found a lateralized posterior negativity between 200 - 300 ms, which was only present during hit trials and was interpreted as attention-related N2pc component (Boncompagni & Cosmelli, 2018). According to Milner and Goodale (2008), the ventral stream is associated with stimulus perception, while the dorsal stream is supposed to underlie motor programming and action. This rather absolute classification has been challenged: both streams appear to be linked to visual awareness (Hesselmann & Malach, 2011), while this link seems to be closer for ventral stream processing (Ludwig et al., 2016). Future studies should examine correlates of target detection during DIB for predominantly ventral features to assess whether the lack of an early correlate during visual DIB could be attributed to the stimulus material. Such an investigation of ERP correlates of awareness during cross-modal DIB, using a ventral target feature (i.e., color change), is currently in preparation by colleagues and myself.

To summarize, the findings regarding electrophysiological NCCs acquired in this dissertation underline an important role of relatively early processes, indicated by a frontal negativity occurring around 200 ms, for auditory target awareness. This frontal ERP component may depict a 'true' auditory NCC, elicited by recurrent processing in auditory cortices, or an essential prerequisite of auditory awareness associated with attentional

control processes and the allocation of attention to the target. The P3 appears to be linked to post-perceptual processing and not awareness per se, contradicting assumptions of the GNW theory – at least in cross-modal stimulus conditions. A sustained negativity in succession to the FN was identified as a candidate for a cross-modal signature of target access.

To advance the search for NCCs further, it is important to continue adapting reliable paradigms to different sensory modalities and to include a variety of stimulus material and different neuroscientific methods in order to reveal the most consistently observed correlates. In addition to looking for ‘final’ answers regarding NCCs, another big open question in the field of consciousness research is the one of the best-fitting theoretical account. Direct comparisons between different theories are required to answer this question (Del Pin et al., 2021). The large Templeton Project (Reardon, 2019) currently taps into this and aims to directly compare empirical evidence for predictions derived from GNWT and Integrated Information Theory (Tononi & Koch, 2015).

### **2.3 Indications of modality-specific differences in the distractor effect**

Despite all stated similarities between the behavioral findings from visual studies and those acquired in Studies I – III, some differences between modalities in addition to the differences in target processing discussed in section 2.2 were observed.

First, differences in the size of the distractor effect could be stated. The effect of distractors on target detection appears to be most pronounced in the visual modality, followed by distractor-induced deafness in cross-modal and auditory conditions (see Table 1). The smallest behavioral effect was observed if a visual target was indicated by an auditory cue (Study III). As thoroughly discussed in Chapter 5, these modality-specific differences seem to rely on the modality of the cue, in combination with particularities of cross-modal processing. An auditory cue appears to be especially efficient in providing a fast release of the negative attentional set and quick attentional allocation to the target. However, the modality of the cue alone cannot explain the observed differences, since unimodal DID

was more expressed than cross-modal DIB, even though an auditory cue was present in both cases. Thus, in addition to potential effects of the modality of the cue, the small cross-modal DIB effect might be explained by an auditory enhancement of visual target detection, which has been observed in previous cross-modal studies (Gleiss & Kayser, 2013; Lippert et al., 2007; Noesselt et al., 2010; Petersen et al., 2017; Van der Burg et al., 2011).

For the related phenomena attentional blink and inattention blindness, it was reported that cross-modal effects tend to be smaller than their unimodal counterparts (Arnell & Jenkins, 2004; Sinnott et al., 2006). It is subject of an ongoing debate (for a review: (Wahn & König, 2017)) whether attentional resources are shared across modalities (Hein et al., 2007; Shomstein & Yantis, 2004; Wahn & König, 2015) or if distinct attentional resources are recruited for each sensory domain (Alais et al., 2006; Arrighi et al., 2011; Duncan et al., 1997; Keitel et al., 2013). Arnell and Jenkins (2004) proposed that both amodal and modality-specific attentional resources with limited capacity exist, which leads to overall more available processing resources under cross-modal stimulation and therefore smaller detection deficits. The findings for DIB/DID are only partly in line with the assumption of larger attentional resources in multisensory settings. While the smallest target detection deficit was found for auditory cue/visual target, cross-modal DID showed a similar, and even slightly larger magnitude than the unimodal auditory effect. Therefore, if the different expression of the behavioral effect in these two cross-modal settings can be replicated, this suggests that an auditory cue leads to a more effective (re-)allocation of attentional resources to a visual target than a visual cue does to an auditory target. The differences between both cross-modal settings despite identical sensory stimulation indicate that cue and target processing might differ systematically between different multisensory settings.

Second, not only hit rates, but also the reliability of response behavior – as indicated by false alarm rates – appears to differ between sensory modalities (see Table 1). More false alarms were produced if an auditory target compared to a visual target had to be detected, in unimodal as well as in cross-modal conditions. These observed differences in response

behavior can neither be attributed to decision speed since responses were always non-speeded, nor to different task instructions, because in all DIB/DID studies participants were instructed to respond as accurately as possible. The modality-specific differences in false alarms might instead indicate that the perceived task difficulty could have differed between tasks involving visual and auditory target detection. In addition to task difficulty itself, the applied decision and response criterion can change based on perceived task difficulty (Brown & Steyvers, 2005; Healy & Jones, 1973). If the DID tasks were perceived as more difficult than the DIB tasks, a more liberal response criterion might have been applied to increase target detection – at the cost of more false alarms. However, this explanation remains speculative since no data on task difficulty and decision criteria during DIB/DID were acquired.

A third difference that can cautiously be stated when comparing behavioral findings between modalities concerns the time course of the effect. Consistently and across modalities, target detection rates are the lowest if cue and target appear concurrently after the presentation of multiple distractors. However, the release of the distractor-evoked inhibition may follow a different time course in different modalities. For visual stimuli, target detection is recovered after 300 - 400 ms (Niedeggen et al., 2012; Sahraie et al., 2001; Winther & Niedeggen, 2018) and a similar release function was found for cross-modal DIB in Study III. In contrast, Studies I and II provided preliminary indications that for auditory targets, the deactivation of the distractor template might not always be completed at a cue-target SOA of 300 ms. In Study II, a significant distractor effect could still be stated at SOA 300 ms for cross-modal DID, while in Study I the tendency to a persisting distractor effect at SOA 300 ms was merely observed on a descriptive level. Future studies should examine the time course of distractor-induced deafness in more detail. A longer-lasting impairment in auditory compared to visual target detection would suggest functional differences in the release of the negative attentional set between both modalities.

In summary, despite many similarities across modalities, some indications of modality-specific differences in the distractor effect can be stated. The magnitude of the target detection deficit, false alarm rates and the time course of the effect may differentiate between different uni- and cross-modal settings. These differences and their assumed underlying causes need to be followed up in future research.

### 3. Limitations and future research perspectives

The following limitations of the studies included in this dissertation need to be considered and should be addressed in future research:

**Awareness ratings.** Throughout all studies, bimodal, non-speeded ratings were used to assess cue and target detection. This response mode requires participants to categorize their stimulus perception into “perceived” or “not perceived” after each trial. The forced-choice responses might lead to guessing in some cases, if the participant is not sure what they saw or heard. Additionally, they rely on the individual response criterion, which might be arbitrary and unreliable (Kim & Blake, 2005). The bimodal ratings were applied to enable a direct comparison to previous visual studies. Participants were always instructed to respond as accurately as possible and false alarm rates were assessed as a measure of response tendencies. It is a topic of debate whether conscious access is an ‘all-or-none’ phenomenon (Dehaene et al., 2017; Del Cul et al., 2007; Sergent et al., 2005; Sergent & Dehaene, 2004), or if it is gradual (Eiserbeck et al., 2021; Fazekas & Overgaard, 2018; Nieuwenhuis & de Kleijn, 2011; Thiruvassagam & Srinivasan, 2021). Some suggest it may even be a mixture of both (Karabay et al., 2021; Sy et al., 2021; Windey & Cleeremans, 2015). If awareness is graded, it cannot be completely depicted by bimodal ratings. One possible avenue for future DIB/DID research could be to capture ambiguous experiences by using a rating scale instead of bimodal ratings, such as the established *Perceptual Awareness Scale* (Overgaard & Sandberg, 2021; Ramsøy & Overgaard, 2004; Sandberg & Overgaard, 2015). Assessing awareness on a graded scale could also provide some information on individual decision

certainty and allow an exploration of possible relations between decision certainty and ERP components, especially the P3.

**Potential confounding processes.** A second critical aspect that needs to be taken into consideration is that awareness as measured in this dissertation may be confounded with other processes such as motor responses, attention, decision processes or the report itself (Aru et al., 2012; Bachmann, 2009; De Graaf et al., 2012). It has been argued that activation differences between perceived and missed stimuli can be attributed either to processes depicting necessary prerequisites of awareness, to true NCCs, or to neural consequences of conscious perception (Aru et al., 2012; De Graaf et al., 2012). This limitation generally applies to studies using the established contrastive approach (Rees & Frith, 2017), relying on the participant's report. It can therefore not be conclusively stated whether the ERP signatures observed in Studies I and II depict prerequisites, true NCCs, or post-perceptual processes. So-called 'no-report paradigms' have been put forward as a potential solution of the confounding of awareness with report (Pitts et al., 2018; Tsuchiya et al., 2015), which try to only rely on objective measures (e.g., eye movements). Nevertheless, these no-report paradigms are not undisputed and not immune to confounds themselves (Block, 2019; Overgaard, 2017; Overgaard & Fazekas, 2016). A promising approach could be to combine conditions requiring and not requiring report in one research design to assess confounds with report (e.g., (Schlossmacher et al., 2021)).

**Samples.** All samples comprised in this dissertation consisted of healthy younger adults (18 – 40 years). We focused on younger participants to avoid potential confounds with age-related processes and due to an easier accessibility of this subgroup of participants. The generalizability of the behavioral and electrophysiological findings is therefore limited to young, healthy adults. NCCs are for the most part investigated in this specific subgroup, raising the question whether older or younger individuals or patients with neurological or psychiatric conditions show the same signatures of awareness. Furthermore, it remains unclear whether DIB/DID can be observed in the same way in other populations. Milders et



al. (2004) reported that a strong individual inhibition ability is associated with a larger DIB in healthy young adults. For older individuals, an age-related decline of the inhibition of distracting information can often be stated (Crawford et al., 2017; Ross et al., 2020), which might affect performance in the DIB task. It could also be relevant to investigate clinical populations with the DIB/DID paradigm, especially patients with inhibitory deficits such as ADHD (Schachar et al., 2000; Woltering et al., 2013) or schizophrenia (Westerhausen et al., 2011). If inhibitory functions are impaired due to a psychiatric or neurological condition, a decreased sensitivity to distractors and therefore a smaller effect of distractors on target detection might be expected. Examining distractor effects in different subpopulations could provide valuable contributions to deciphering the impact of irrelevant stimuli on perception and to understanding the underlying mechanisms. In return, a thorough understanding of inhibitory processes will provide the necessary foundation for developing purposeful treatment options for patients who suffer from impaired inhibitory functioning.

**Content-specific vs. full NCCs.** Koch et al. (2016) proposed a differentiation between full NCCs, describing neural processes that underlie conscious perception in their entirety, and content-specific NCCs, comprising all neural activity evoked by perceiving (vs. missing) a specific stimulus. It is therefore important to consider that, following this distinction, Studies I and II assessed content-specific NCCs. The vast majority of research in the field shares this limitation. Individual findings can be influenced by the stimulus material (Boncompagni & Cosmelli, 2018; Rutiku et al., 2016), restricting comparability between studies. Consequently, it appears essential to accumulate findings using different paradigms and stimuli to assess which candidate NCCs can be most consistently observed – and therefore may provide ‘full’ NCCs. Studies I and II provide a contribution to this accumulation of scientific findings outside of the best-studied visual modality.

**Processes underlying ERPs.** The examination of ERPs provides a well-established, valuable method to investigate cognitive mechanisms and their neural underpinnings with a high temporal resolution (Luck, 2005). Limitations of this neuroscientific method, which was

applied as a key method in this dissertation, are the low spatial resolution, that only cortical potentials can be recorded, and the question of the interpretation of the observed ERP components (Kappenman & Luck, 2016). One ERP component might depict different cognitive processes in different tasks and could be influenced by a variety of factors (Kappenman & Luck, 2016; Luck, 2005). Based on ERP data alone, it cannot be conclusively stated which brain areas or networks cause the activation depicted in a component and which processes are at the basis of this event-related spike in neural activity. The latter can only be reasonably suspected based on previous findings, which limits the objectivity and explanatory power of individual neuroscientific findings.

**Individual distractor sensitivity.** Throughout all studies, it was observed that some participants appear to be somewhat ‘immune’ to distractors and show no or only a marginal target detection deficit after multiple distractors. In contrast, other participants exhibit a very pronounced reduction of hit rates in the multiple compared to the zero distractor condition (i.e., >50%). We explicitly addressed this observation in Study II, where the “distractor-insensitive” subjects with less than 10 misses in the multiple distractor condition were included in additional analyses. Nevertheless, the data acquired in Study II did not allow conclusions about potential causes of the differences in distractor sensitivity. It therefore remains unclear which factors determine the individual sensitivity to distractors during DIB/DID and if these factors are consistent across sensory modalities. In the visual modality, a larger DIB was correlated with a strong inhibitory ability as measured with the Stroop task (Milders et al., 2004). For attentional capture, it has been stated that a higher working memory capacity might be related to a faster recovery of the distractor effect (Fukuda & Vogel, 2011), while the individual size of the attentional blink is apparently influenced by executive working memory functioning and the attentional focus (Willems & Martens, 2016). Future research is needed to determine individual factors underlying the individual susceptibility to distractors and the recovery of the effect in different modalities. Another interesting research question might be whether the individual distractor sensitivity can be influenced by training, e.g., by repeatedly performing a DIB/DID task over time.

#### 4. Conclusion

Distracting stimuli have a profound influence on the detection of subsequent, task-relevant information – not only in visual but also in auditory and auditory-visual stimulus conditions. The findings of all studies included in this dissertation consistently showed that multiple distractors, which possess the target's features, impair target detection in different sensory modalities. This impairment is especially pronounced if the cue, functioning as a signal of task relevance, and the target appear in close temporal proximity. The phenomenon of distractor-induced deafness (DID) was established and the transferability of distractor-induced blindness and the underlying model to different sensory modalities was demonstrated. The results suggest that distractor-driven inhibitory processes work in a similar manner across sensory domains. However, some modality-specific differences were observed and need to be considered.

Contributing to the search for auditory signatures of awareness, a central finding was that an early frontal ERP component was linked to auditory target access in both auditory and cross-modal setting. Auditory awareness therefore appears to depend crucially on this relatively early process. Whether the early negativity depicts consciousness perception based on sensory processing or attentional control processes necessary for target awareness remains to be dismantled. A sustained and widespread negativity in succession to the early frontal process was observed as a candidate for a cross-modal marker of auditory awareness. For the P3, which has been proposed as a reliable late ERP correlate, the results were inconsistent: while an enhanced P3 for detected targets was observed as second correlate in the auditory modality, no comparable P3 enhancement was found during cross-modal DID. Instead of being associated with awareness itself, the P3 and its underlying processes appear to depict subsequent post-perceptual processing linked to decision processes in the cross-modal setting.

The quest for neural correlates of consciousness is ongoing, as is the search for a unanimous, scientific definition of the phenomenon of consciousness, encompassing all its

facets. A large amount of multidisciplinary research has been inspired by the topic of human consciousness, which still carries many mysteries. Combining different neuroscientific methods and a variety of experimental approaches in different sensory modalities will contribute to gradually resolving some of these mysteries.

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**CURRICULUM VITAE LEA KERN**

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For reasons of data protection, the Curriculum Vitae is not included in the online version.

### List of publications

**Kern, L., & Niedeggen, M. (2021).** Distractor-induced deafness: The effect of multiple auditory distractors on conscious target processing. *Cortex*, 134, 181-194.  
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## Anteilserklärung

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- Entwicklung der Konzeption (in Teilen)
- Literaturrecherche (mehrheitlich)
- Versuchsdesign (in Teilen)
- Datenerhebung (vollständig)
- Datenauswertung (in Teilen)
- Ergebnisdiskussion (mehrheitlich)
- Anfertigung der ersten Version des Manuskripts (vollständig)
- Einreichung des Manuskripts und Korrespondenz (mehrheitlich)
- Überarbeitung des Manuskripts (mehrheitlich)

Study II: Kern, L., & Niedeggen, M. (2021). ERP signatures of auditory awareness in cross-modal distractor-induced deafness. *Consciousness and Cognition*, 96, 103241. <https://doi.org/10.1016/j.concog.2021.103241>

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- Einreichung des Manuskripts und Korrespondenz (vollständig)
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- Entwicklung der Konzeption (in Teilen)
- Literaturrecherche (vollständig)
- Versuchsdesign (mehrheitlich)

- Datenerhebung (vollständig)
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Berlin, März 2022

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Lea Kern

Ich bestätige die obenstehende Anteilserklärung:

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Michael Niedeggen

**Eigenständigkeitserklärung**

*Eidesstattliche Erklärung nach § 7 Abs. 4 der Gemeinsamen Promotionsordnung zum Dr. rer. nat./Ph. D. des Fachbereichs Erziehungswissenschaft und Psychologie der Freien Universität Berlin vom 8. August 2016:*

Hiermit versichere ich, dass ich die vorliegende Arbeit selbstständig und ohne unerlaubte Hilfe verfasst habe.

Alle Hilfsmittel, die ich verwendet habe, habe ich angegeben. Die Dissertation ist in keinem früheren Promotionsverfahren angenommen oder abgelehnt worden.

Berlin, März 2022

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Unterschrift Lea Kern



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