Auditory distraction during visuomotor steering

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ABSTRACT

Auditory distraction, the involuntary processing of unexpected sounds, allows us to become aware of changes in our environment that otherwise might go unnoticed. For example, while being focused on the road ahead, the sound of a car horn might warn us from an approaching car that we would have neglected, without auditory distraction. It is assumed that distraction occurs when an event violates our expectations about our auditory environment. For example, in auditory oddball tasks, sounds with a lower probability of occurrence are less expected and, thus, are reliably shown to be processed preferentially, reflected in increased measured brain potentials (i.e. event-related potentials (ERPs)), relative to expected sounds. However, besides the probability of occurrence, it was recently suggested that also the local short-term context in which an event occurs, as well as expectations that are based on our long-term memory content, influence our expectations and thus define auditory distraction.

In the first part of the current dissertation, I provide evidence to support this assumption. Both, the physical difference of an unexpected event from its short-term context as well as its difference from long-term memory expectation were shown to result in increased processing of the eliciting event, as reflected in enhanced brain potentials. The increased processing of an unexpected auditory event also increases its demand for attentional resources and, thus, can decrease the performance in simultaneously performed tasks. It is, however, still under debate whether auditory distraction places a demand on general resources that are shared between sensory modalities or whether this demand is specific to the auditory modality. In the current dissertation, I argue that both is possible. Events that are distracting, due to their difference from their short-term context, increased the demand for general attentional resources that are shared between the auditory modality and a visually presented visuomotor control task. Events that are distracting because they differ from our long-term memory expectations increase the demand for modality-specific attentional resources.

But attentional resources are not only involuntarily attracted by unexpected auditory events. It is also possible to voluntarily attend to relevant events or tasks. While most research is devoted to study either voluntary or involuntary attentional processing, recent evidence suggested that both processes might interact. Indeed, in the second part of my dissertation, I show that increased demands, in a voluntarily performed visuomotor control task, can decrease the involuntary auditory distraction. More specifically, this is only the case for such demands which are known to increase the demand for "perceptual-central" resources. Furthermore, I show that a decrease of auditory distraction can not only result from high task demands, but also occurs in cases in which the auditory modality is perceived as being irrelevant.

CONTENTS

ABBREVIATIONS

DP	Distraction Potential
EEG	Electroencephalography
ERP	Event-Related Potential
MMN	Mismatch Negativity
MUA	Mass Univariate Analysis
RON	Reorientation Negativity
RT	Reaction Time

1 INTRODUCTION

1.1 Why we should (not) be distracted by auditory information during the control of a vehicle — and do we have a choice?

The auditory modality can be referred to as the 'alarm sense' of the human. The reason for this is that we are particularly well able to detect unexpected changes in our environment when these changes are auditory in nature. The special role of the auditory modality is justified because we can hear objects or threats, even when they are out-of-sight (in contrast to vision) and beyond reaching distance (in contrast to somatosensation). For this reason, most warnings are auditory. An example for this is the car horn that can warn other road users, regardless of their line-of-sight. However, car horns are only effective if the warned road users are able to orient their attention to the source of the unexpected auditory event and to decide, in a fraction of a second, whether and how to respond to it.

Given the limited attentional resources, we might expect a deterioration in our ability to perform our main task when unexpected auditory events capture our attention. This suggests a conflict between the necessity to detect and process unexpected events and the necessity to focus our attentional resources on the main task to preserve its performance. These two conflicting aspects can be conceptualized as two mechanisms that compete for the control of our limited attentional resources. First, the mechanism to detect and process unexpected events. This mechanism orients our attentional resources, involuntarily, to the unexpected event and is mostly driven by factors that are referred to as exogenous, such as the loudness of the unexpected event (e.g. Santangelo and Spence (2009); Escera and Corral (2003)). The second mechanism that competes for the control of our limited attentional resources is the mechanism that allows us to focus on the main task. This mechanism allows us to, voluntarily, focus the attentional resources on aspects of the main task, depending on endogenous factors, such as our task goals (e.g. Peelen et al. (2004); Hopfinger and West (2006)). As both mechanisms share the same limited attentional resources, we need to maintain a balance between them.

This balance has to be maintained not only within a single sensory modality but also across modalities. Processing unexpected auditory events can interfere with tasks that do not have an auditory component. One such task, which is of particular interest for the current dissertation, is the visuomotor control task, such as when we drive a car. There, it is crucial that we detect and recognize unexpected events in our environment (e.g. the warning car horn or environment sounds) while we continuously maintain stable control of our vehicle. Nonetheless, increased visuomotor control demands can hamper our ability to detect and recognize auditory events, such as warning sounds (Dehais et al., 2014, 2016; Giraudet et al., 2015). Conversely, unexpected auditory events can distract our visuomotor control performance (Ranney, 2008; Ranney et al., 2000; Lee, 2014). What causes this to happen?

The current dissertation examines the factors that determine whether unexpected auditory events are detected and processed, despite the demands of a concurrently performed visuomotor control task. In the first part, which consists of Chapter 2 and the appendix in Chapter 5.1, I examined the influence of exogenous factors that concern the properties of the unexpected auditory event. In the second part, which consists of Chapter 3 and Chapter 4, I examined the influence of endogenous factors, such as the voluntary goals of the participants. In more detail, I address the influence of the auditory context in which the events are presented (Chapter 2) and the events' familiarity (Chapter 5.1) on their likelihood to be processed, despite the concurrent demands of a visuomotor control task. Next, I address whether the involuntary processing of these events depends on different types of task demands (Chapter 3) and the task relevance of the auditory modality (Chapter 4).

An overview and discussion of all the experiments can be found in Section 1.5. The remainder of this chapter will introduce the core concepts of visuomotor control to the reader (1.4), the processing of unexpected auditory events (1.3) and how limited attentional resources might be shared between visuomotor control and auditory processing (1.2).

1.2 AUDITORY DISTRACTION AND VISUOMOTOR CONTROL — THEIR COMPETITION FOR ATTENTIONAL RESOURCES

This section introduces the core concept of task demands and attentional resources. It is meant to facilitate the understanding of how visuomotor control and the processing of unexpected auditory events might interfere with each other.
Generally, visuomotor control and the processing of auditory events interact if (i) resources or cognitive structures are shared between both and (ii) the added demands for these resources or cognitive structures exceed its availability.

1.2.1 *From one-channel model to multiple resource theory*

The observation that we are limited in our ability to perform several tasks in parallel, such as the processing of an unexpected auditory event during the performance of a visuomotor control task, is not new. Early on, researchers were interested in understanding whether, and how, the parallel processing of tasks, or stimuli, is possible in human cognition and what would limit its success.
An early attempt to model the human ability to process tasks, or stimuli, in parallel was made by Broadbent. He assumed that the parallel processing of stimuli is possible until a certain point in the cognitive processing chain. From this point on, which is also referred to as bottleneck of cognitive processing, stimuli are processed only in series (Broadbent, 1957; Welford, 1967; Broadbent, 1971). More specifically Broadbent (1971) suggested a processing system that consisted of three elements: (i) a short-term store that allows the parallel sensory registration of all incoming stimuli, (ii) a selective filter that can be set by the observer to any task-relevant feature (i.e. stimuli with task-irrelevant features are filtered out and not processed), and (iii) a limited capacity channel that processes stimuli in series.
Applied to the processing of auditory events during the performance of a visuomotor control task, Broadbent's model would make the following prediction: Initially, the auditory event and the visual input from the control task would be registered in the

short-term store, in parallel. Subsequently, the setting of the selective filter would determine whether the auditory event or the visual input would continue to be processed through the limited capacity channel. More specifically, if the filter is set to selectively process auditory events, the processing of the visual input would be interrupted, for the time period when the auditory event is processed. If, instead, the filter is set to process the visual input, the auditory event would be lost or delayed.

Broadbent's model has been modified and extended since its conception. For example, there is evidence to suggest that irrelevant stimuli are only attenuated and not filtered out completely, as Broadbent's original model would suggest (Moray, 1959). With this modifications, Broadbent's basic model continues to be useful in order to address how the processing of two stimuli, or tasks, interfere.

Broadbent's model is a structural model that assumes that tasks interfere when they compete for use of a shared cognitive structure. In contrast, a different type of model assumes that concurrently performed tasks interfere when they compete for shared attentional resources, and therefor are referred to as resource models (Kahneman, 1973; Moray, 1967).Resource models have two basic assumptions in common. First, they assume that attentional resources are limited and, second, that the processing of stimuli consumes these attentional resources, hence reducing its overall capacity (e.g. Navon and Gopher (1979); Wickens (1976); Kantowitz and Knight (1976); Polson and Friedman (1988); Boles and Law (1998)). As will be described later in more detail, when two tasks compete for the same resource their overall performance decreases, relative to a situation in which both tasks are performed in isolation.

Resource models can be further divided into two categories. First, there are unitary resource models that are based on the assumption that only one pool of attentional resources exists, which is shared between all tasks that are performed in parallel, even across sensory modalities (Kahneman, 1973; Moray, 1967). Second, there are multiple resource models that are based on the assumption that several pools of attentional resources exist (Navon and Gopher, 1979; Wickens, 1976; Kantowitz and Knight, 1976). According to the multiple resource models, tasks that are performed in parallel only compete for the same attentional resources, if they require resources from the same pool, while according to unitary resource models tasks that are performed in parallel always compete for attentional resources. This difference has important practical implications for possible interferences between visuomotor control and auditory processing. While unitary resource models predict a competition for attentional resources whenever the added demands of the visuomotor task and auditory processing exceeds the overall capacity of available resources, multiple resource theories predict that a competition will only occur when the same resource is required by both tasks.

Multiple resource models are currently favored over unitary resource models, given that they can better account for experimental results, for example in dual-task studies. Indeed, the competition for attentional resources, between two concurrently performed tasks, does depend on the specification of both tasks. The more similar both tasks are, the more they compete for attentional resources. For example, when two concurrently performed tasks require a manual motor output they interfere more than when one requires a manual and the other one a vocal output (Mcleod, 1977). Within the framework of multiple resource models, these results suggest that the generation of a manual output, on the one hand, and the generation of an vocal output, on the other, require resources from separate pools of resources, while unitary resource models cannot readily account for these results.

One influential multiple resource model is developed in the multiple resource theory by Wickens (1980, 2002). Here, Wickens suggests four dimensions of resources that are depicted in Figure 1 :(i) the dimension of processing stage, which is divided into perceptual/cognitive and response stage, (ii) the dimension of sensory modalities, which is divided into auditory and visual, (iii) the dimension of processing code, which is divided into: spatial/manual and verbal/vocal and (iv) the dimension of visual processing, which is divided into: focal and ambient processing in the visual modality (not depicted in Figure 1). However, the division of resource pools is controversial. Although most researchers agree with the existence of multiple pools, some suggest a different division of these pools, for example, based on cortical hemispheres (Polson and Friedman, 1988) or sensory modalities (Boles and Law, 1998).

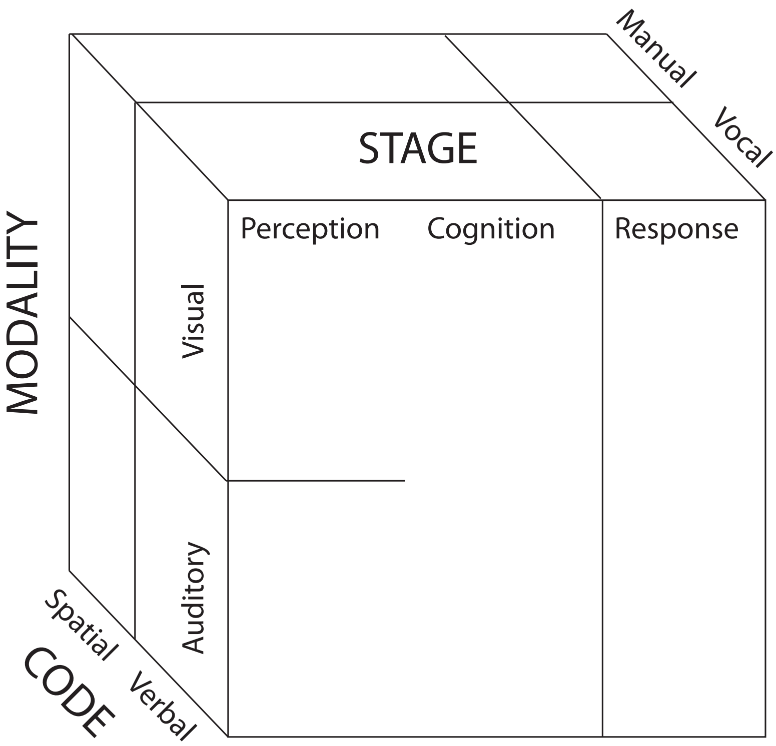

Figure 1: Multiple resource model, after Wickens (2002), with the three dimensions: Processing stage, modality, code. The forth dimension, visual processing is nested within the visual modality and is not depicted in the figure

1.2.2 *Task demands and attentional resources*

In the previous subsection, I established that within the framework of multiple resource theories, two tasks, such as the visuomotor control task and the detection of an unexpected auditory event, can interfere if they require attentional resources from the same pool of resources. However, whether both tasks indeed interfere depends on the amount of attentional resources that both require. Only if the added demand of both tasks together requires more attentional resources than we have at our disposal, they will interfere (Wickens, 2002; O'Donnell and Eggemeier, 1986). Thus the risk for an interference increases, when the demands of one, or both, of the involved tasks increases. With the aim to monitor such an increase in demands, different measures have been developed. In the following, these measures are described in short.

Subjective measures: This measurement technique is based on the assumption that participants are able to perceive a change of demands and to report this perception in questionnaires (Yeh and Wickens, 1988). Well-known examples of such questionnaires are the NASA task load index (NASA-TLX; Hart and Staveland (1988)), the multiple resource questionnaire (MRQ) (Boles et al., 2007) and the simple rating scale mental effort (RSME) (Zijlstra, 1993). However, such measures of perceived task demands are intrusive in the sense that it is demanding for participants to rate their load while they are involved in the task. If the perceived demands are rated after the completion of the task, in order to avoid intrusions, the ratings can be biased due to its retrospective nature (Young et al., 2015).

Behavioral measures in the main task: A typical observation, from everyday life, is that increasing the demands of a task leads to a decrease in our ability to perform this task. For example, if vehicle control is more demanding because of icy roads, one would expect lane-keeping to worsen, relative to dry road conditions. However, this common observation only represents part of the truth. Theoretical hypothesis (Meister, 1976; North et al., 1979) and experimental evidence (Cassenti, 2006; Cassenti et al., 2013) have shown that task performance is not a linear function of the task's demands, which is illustrated in Figure 2. When the task demands are generally low, an increase in demands does not have a direct influence on the performance. In Figure 2 this is depicted in region A. Here, there are enough attentional resources to cope with an increase in demands. When the demanded resources exceed its capacity, performance can no longer be maintained. That is the point when performance drops and we enter region B. Only in region B, is performance a monotonic function of task demands. Finally, in region C, task demands are so high that the performance has reached its minimal limit. Again, an increase in task demands does no longer result in a monotonic performance decrease. This means that the performance in a task, such as the visuomotor control task, does not always reflect the amount of attentional resources it consumes.

Behavioral measures in an additional task: As described throughout this section, increased demands in the main task can also hamper the processing of secondary stimuli, such as unexpected auditory events. The reason for this is that processing such secondary stimuli depends on residual attentional resources that are not required by the main task.

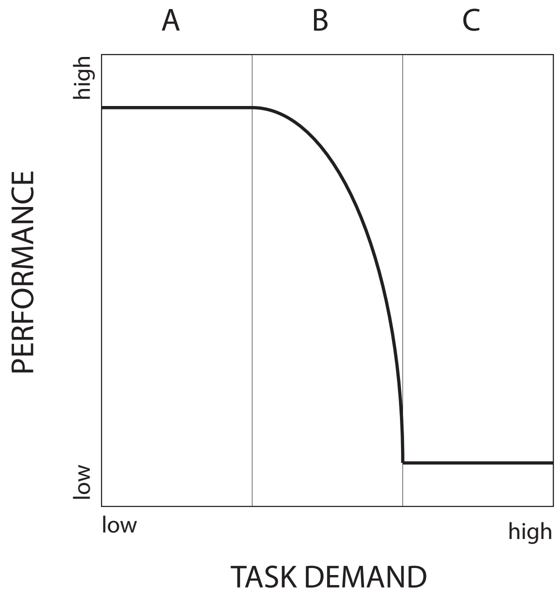

Figure 2: Relationship between task demand and performance, after O'Donnell and Eggemeier (1986) with three regions of task demands: A: low task demands, B: medium task demands and, C: high task demands.

These residual resources decrease with an increase of task demands, even when there is no observable change in the main task's performance. On the behavioral level, this can be reflected, in an increase in reaction time and a decrease in detection sensitivity to secondary task stimuli (Kida et al., 2004; Isreal et al., 1980).

Physiological measures — the event-related potential (ERP): However, such performance decrement to secondary stimuli is only a consequence of the decreased processing of secondary stimuli, such as the processing of an unexpected auditory event. This deterioration in auditory processing can also be measured more directly from decreased brain responses, which accompany the processing of auditory events. The event-related potential (ERP) (see, Section 1.3) is such a brain response that is elicited by the occurrence of an auditory event. It has been repeatedly shown that when an auditory event is processed less, due to a reduction in overall resource availability, the measured ERP is reduced as well (e.g. (Kramer et al., 1983; Wickens et al., 1983; Sirevaag et al., 1989; Kida et al., 2004)).

1.2.3 *Summary*

In summary, the current section showed that visuomotor control and the processing of unexpected auditory events can interact if both require the same type of attentional structures or resources and, furthermore, if task demands for limited attentional resources are sufficiently high. An increased resource competition can have different measurable consequences. First, participants can perceive the increased demand and report it in questionnaires. Second, the performance in the main task can, but does not have to, decrease with changes in its demands for resources. Third, our ability to perform additional tasks decreases with increased task demands. Forth, secondary events are processed less.

1.3 Auditory distraction — the involuntary processing of unexpected auditory information

This section outlines the mechanisms which underlie the involuntary processing of unexpected auditory events. Furthermore, factors that can advance this involuntary processing are described, together with methods to measure its occurrence.

1.3.1 *The voluntary and involuntary allocation of attentional resources*

In Section 1.2 I described that the processing of an unexpected auditory event depends critically on the availability of attentional resources. If fewer attentional resources are available, for example, because we are involved in an increasingly demanding task, the processing of unexpected auditory events is at a risk to be impaired. But even if enough attentional resources are available, this is not a guarantee that unexpected auditory events are processed. Instead, we only process unexpected auditory events if our available attentional resources are allocated for their processing. This might sound trivial. However, we are typically surrounded by such a wealth of information that it would exceed the availability of our attentional resources, by far, to fully process everything. Due to this reason, only a small portion of the information in our environment is selected for processing. This selection is assumed to depend on two opposing mechanisms. The voluntary, or endogenous, control of attention and the involuntary, or exogenous, control of attention (Eimer et al., 1996; Posner, 1980). These two mechanisms compete for the control over the limited attentional resources.

Voluntary control of attention refers to the selection and attentional processing of an event, or stimulus, based on one's intentions. The voluntary control of attention has been often studied in visual search tasks. In such tasks, participants try to find a visual target stimulus, for example, the letter 'T', as fast as possible. If in such a visual search task a cue, such as a centrally presented arrow, informs the participants about the target's location they are able to voluntarily allocate their attentional resources to the cued location. This is consistently reflected in faster and more accurate reactions, relative to the same stimulus at an uncued location (Hopfinger and West, 2006; Arnott et al., 2001).

Involuntary control of attention, on the other hand, refers to the selection and attentional processing of an event or stimulus, that is salient, such as a loud sound with sudden onset, and that attracts attentional resources involuntarily. If such a stimulus is presented at the location of a target stimulus, in a visual search task, it can result in similar performance improvements as described for its voluntary counterpart (Santangelo and Spence, 2009; McDonald et al., 2000, 2005). The involuntary attention control, also termed distraction, is often described as a three-staged process, which is depicted in Figure 3, A: (e.g. Wetzel and Schröger (2014); Escera and Corral (2007); Horváth et al. (2008)).

At the first stage of distraction, we detect the unexpected auditory event. Experimental evidence suggests that this detection is independent of the availability of attentional resources (SanMiguel et al., 2008; Harmony et al., 2000; Näätänen and Winkler, 1999). This means that even when we are involved in a demanding task, we are able to detect unexpected events in our environment. It is important to note that the classification of an event as 'unexpected', implies the existence of expectancies towards our auditory environment. Indeed, it is widely acknowledged that we continuously code the regularities of our auditory environment into a predictive model (Schröger et al., 2015b,a; Bendixen et al., 2012; Baldeweg, 2006). Detected events are compared against the predictions, which

are derived from this predictive model. The more an event differs from our predictions, the more it surprises us and, thus, is likely to reach the second stage of distraction.
In the second stage of distraction, we orient our attentional resources towards the detected event. Different than the detection stage, this stage is assumed to consume attentional resources. For this reason, only a limited number of events can reach this second stage. Furthermore, the consumption of attentional resources by the unexpected event reduces the availability of attentional resources and, thus, can deteriorate the performance in a, concurrently performed, task (SanMiguel et al. (2008); Berti and Schröger (2003); Spinks et al. (2004); Muller-Gass and Schröger (2007) and see 1.2).
After we fully processed the unexpected event, the third stage of distraction terminates the distraction process. We orient our attentional resources away from the unexpected event and, if applicable, back to the task that we are currently involved in.

According to this three-staged distraction model, a competition for attentional resources

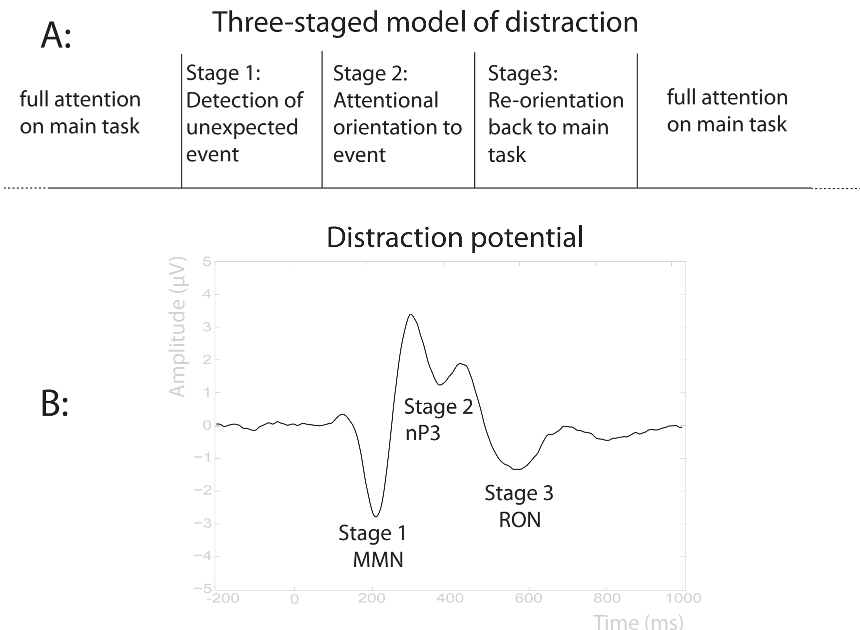

Figure 3: A: Three-staged model of distraction after Näätänen (1990). The three stages of distraction in successive order and short description, B: The distraction potential, an ERP that accompanies the three stages of distractions

between our voluntary and involuntary attentional control only occurs at the second stage, when our attentional resources are oriented to the unexpected event for its processing. It is important to note that each of the three stages of attentional orienting correspond to a component of the ERP (see, Figure 3, B:) and, thus, can be monitored individually.

1.3.2 *Factors that define the strength of involuntary attention control*

Which factors determine whether we do not only detect an auditory event but involuntarily spend our limited attentional resources for its processing, even at the expense of performance decrements in our main task?

Factors which are known to have this effect, can be either specific or aspecific to the auditory event (Eimer et al., 1996; Hughes, 2014). Factors that are aspecific to the auditory event concern the relation of the auditory event to its surrounding. It is well corroborated that events that violate established regularities in our environment are likely to attract attentional resources (Schröger et al., 2015b,a; Bendixen et al., 2012; Baldeweg, 2006). As mentioned in the previous subsection, this was taken as evidence for the existence of a predictive model that generates, based on the regularities in our environment, expectations concerning future events. For example, participants process a female voice more when it is presented in a series of male voices than when it is presented in a series of female voices (Hughes et al., 2013). The reason for this is that in the former case the participants expect, based on their predictive model, the occurrence of another male voice, while in the latter case the predictions match the actual auditory event.

Specific factors, in contrast, are inherent to the auditory event, such as its familiarity or personal significance (Hughes, 2014). The fact that familiar and personal significant events are processed preferentially, was taken as evidence that the predictive model, against which the auditory event is compared, also includes long-term memory representations (Schröger et al., 2015a). This is reflected, for example, in the preferential processing of our own name (e.g. Moray (1959); Berlad and Pratt (1995)), our own ringtone (Roye et al., 2010) or words spoken in a voice that is familiar to us (Holeckova et al., 2006), relative to events without personal significance.

1.3.3 *Measuring involuntary attentional processing*

In order to study how attentional resources are involuntarily allocated towards unexpected auditory events, we need a technique to measure their processing. Unexpected auditory events, which are involuntarily processed, often do not require an overt and measurable response. For this reason, we cannot assess their processing via performance measurements. Instead, typically one of the following three techniques are used:

The reported perception of the unexpected auditory event: Some researcher used their participant's reported perception of the unexpected auditory event as a measure of the processing of the respective event (e.g. Koreimann et al. (2014); Macdonald and Lavie (2011); Dehais et al. (2014)). Different than the other measurement techniques, the reported perception of an event allows investigating whether unexpected events are consciously perceived by the participants. Drawbacks, however, are that the unconscious processing of events cannot be measured and that this measure does not allow to assess the individual processing stages of auditory distraction, for example, based on the three-staged distraction model.

The behavioral distraction, by the unexpected auditory event: If participants are involved in a task, the processing of unexpected auditory events can measurably distract the participants' performance. This is presumably the case because attentional resources, which are vital for stable task performance, are attracted by the unexpected events. In the past, the behavioral distraction has been used as index for involuntary attentional control and was shown to reflect the involuntary processing of the unexpected auditory events (Roberts et al., 1994; Hester and Garavan, 2005; Lavie et al., 2004; Lavie, 2005; de Fockert et al., 2000). It is important to note that it has been recently shown that this is only the case if the unexpected event contains some information about the task at hand (Parmentier et al., 2010; Wetzel et al., 2012). This is, for example, the case if the unexpected auditory event is presented a fixed time-interval ahead of a task-relevant event and thus informs the participants about its occurrence.

The response of the participants' brain to the unexpected auditory event (i.e. the ERP): The allocation of attentional resources towards unexpected auditory events is also accompanied by a fluctuation in the brain's electrical potential, which can be measured as ERP at the scalp, as depicted in Figure 3, B: (e.g. Escera et al. (1998); Rinne et al. (2006); Berti et al. (2004); Escera et al. (1998); Friedman et al. (2001)).

When the brain processes any kind of event, this is based on changes in the electrical state of single neurons. This changed electrical state results in a propagation of current through the conductive matter of the brain's tissue. Under certain circumstances, which include the number, location, and orientation of activated neurons, this can change the electrical potential at the scalp, which we can measure via skin electrodes. The first to describe such measurable scalp potential changes, termed electroencephalogram (EEG), was Berger (1929).

However, the EEG does not only contain the electrical potential changes that characterize the brain's response to the unexpected auditory event, which we are interested in. Instead, it is a mixture of all processes that are executed in the brain. For this reason, we cannot readily identify one single cognitive process, like the processing of an unexpected auditory event, in the EEG. In order to extract that specific process, we need to make sure that all aspects of the signal, which are unrelated to the unexpected auditory event, are removed. For this purpose, we present the unexpected event repeatedly (between 50-150 repetitions) and record the EEG signals that are time-locked to each of these presentations. By averaging over these time-locked EEG signals, only the aspects of the signal that are related to the repeated auditory event remain.

After averaging, the ERP shows a pattern of positive and negative components (see, Figure 3, B). In this figure, the unexpected event was presented at time-point zero. By following the time-axis to the right, we can track the electrical potentials that were, one after the other, elicited by the brain. Traditionally, the components in the ERP waveform are labeled according to their polarity, with P and N, indicating a positive or a negative deflection, respectively. The number indicates the position of the peak within the waveform (e.g. P1 is the first positive wave, P2 the second, and so on). However, differing labelling conventions exist that use the number to indicate the latency of the respective peak (e.g. P300 for a positive component at 300 ms) or to describe the underlying component (e.g. mismatch negativity (MMN) for a negative deflection which is elicited when a detected event mismatches the predictions of the predictive model).

The ERP is an important tool for scientific research because ERP components can be linked to experimental manipulations of established cognitive processes. For example, as mentioned earlier, the MMN is elicited when a detected event violates our expectations, which are generated by the predictive model (Escera et al., 1998; Rinne et al., 2006), while the same event's P300 reflects the updating of the working memory context based on this event's information content (Donchin, 1981). Based on this, we can use a change of the amplitude, or latency, of such an ERP component, to index the strength, or duration, of the related cognitive process.

For the assessment of auditory distraction, it is important to know that the three-staged distraction process is accompanied by a specific sequence of ERP components, which is termed distraction potential (Escera and Corral, 2003). Each ERP component of this distraction potential, which is depicted in Figure 3, B, was suggested to reflect one of the stages of auditory distraction. The first stage of distraction, the detection of an unexpected event, is accompanied by the negative MMN, which peaks 100-250 ms after the stimulus onset (Näätänen et al., 1978; Winkler et al., 1998).

The MMN is followed by the positive P3a, or novelty-P3, which peaks after 250-400 ms and reflects the attentional orientation to, and cognitive processing of, the unexpected event (Berti et al., 2004; Escera et al., 1998; Friedman et al., 2001; Polich, 2007). Interestingly, in the recent years, it has been shown that the novelty-P3 consists of two separate subcomponents, the early and late novelty-P3 (Escera et al., 1998, 2001; Yago et al., 2003). Chapter 3 offers possible functional underpinnings for these subcomponents of novelty-P3.

The last component of the distraction potential is a negative peak after 400-600 ms. This component is termed re-orientation negativity (RON) and reflects the re-orientation of attention, back to the main task (Schröger et al., 2000; Schröger and Wolff, 1998b).

1.3.4 *Summary*

In summary, in the current section, I showed that attentional resources can be involuntarily captured by auditory events that violate the predictive model of the environment or are familiar and of personal significance. Furthermore, I showed that unexpected auditory events are processed in three consecutive stages. These stages are accompanied by the components of the distraction potential, which is a characteristic ERP waveform. This distraction potential allows to monitor the processing of unexpected auditory events, for example during the performance of a visuomotor control task.

1.4 Visuomotor control — how visual information is transformed into motor control

In this section, I outline our understanding of visuomotor control — the utilization of visual information for a motor control output. Furthermore, I introduce a commonly used model for visuomotor control, namely the closed-loop control model. I conclude the section with an overview of insights from previous literature about how visuomotor control demands can hamper our ability to allocate attentional resources towards auditory events.

1.4.1 *Visuomotor control: the transformation of visual information into motor control*

The visuomotor control of an object, such as the control of a vehicle by a driver, relies on the accurate visual perception of relevant information in order to trigger the appropriate motor output. The neural processing of visual information is assumed to take place in two distinct visual pathways, that are termed dorsal and ventral stream (Ungerleider and Mishkin, 1982; Goodale and Milner, 2003). Both originate from a common source in the primary visual cortex and process different aspects of the visual information. Importantly, these two pathways do not only play an important role in visual perception. Instead, Goodale recently suggested that these two pathways also play a major role in the transformation of visual information into a motor output, and thus enable visuomotor control (Goodale, 1998; Goodale and Westwood, 2004). The dorsal stream, which the authors termed action stream (Goodale, 1998), utilizes the incoming visual information, to directly trigger a motor output. The ventral stream, in contrast, is traditionally characterized as the stream that provides our visual perception of objects and events (Goodale and Milner, 2003). For example, if we are sitting in a car and looking out of the windscreen, it provides us with the information of the trajectory of the road ahead of us, as well as of obstacles, such as pedestrians or other cars. In order to effectively control our vehicle, we need to transform this percept into a motor action, which will change the steering wheel's angle in order to follow the perceived road and to avoid the perceived obstacles. Informed by the ventral stream, the visuomotor networks in the dorsal stream, which are mostly located in the posterior parietal cortex (Culham et al., 2006), converts the trajectory of the road into an appropriate motor action.

Thus, on the neural level, visuomotor control requires that the visual information is transformed, via the dorsal stream, into a motor output. In this process, the ventral stream can provide additional information about the objects that are involved in the visuomotor control task.

1.4.2 *The closed-loop control task: A model for visuomotor control in steering*

The provided description of visuomotor control, based on the neural transformation of visual information into a motor output, is only one way to describe the visuomotor control task. Based on the field of research and the scientific questions, different models emerged that describe different aspects of visuomotor control.

From a human factors point of view, specific tasks that fall under the category of visuomotor control are considered. One such task, which gained considerable scientific interest, is the task of steering a vehicle (e.g. Walter et al. (2001); Reed and Green (1999); Briem and Hedman (1995); Groeger (2000)). The aim of modelling this task was to generate a "knowledge and rule based model of the driver that will be capable of dealing with a wide variety of realistic, complex situations" (Michon (1985), page 486). In order to do so, besides the visuomotor control of the vehicle itself, two more levels were considered to describe the task of the driver: the strategic level and the maneuvering level (Peters and Nilsson, 2007; Michon, 1979, 1985). On the strategic level the driver has to decide about aspects of the task such as the type of vehicle, the route to take or the involved risks, on the maneuvering level, single maneuvers, such as obstacle avoidance or overtaking are defined. The visuomotor control is in this model considered as the lowest level, which defines individual motor actions, such as the change in steering wheel angle. From an engineering point of view, visuomotor control has been described in different types of models that allow the mathematical description of the human, the object that is controlled by the human and their environment, often in the background of driving a car or piloting an airplane. Examples of such models are the open- and closed-loop control models. Both of these control models are shown in Figure 4. Open- and closed-loop

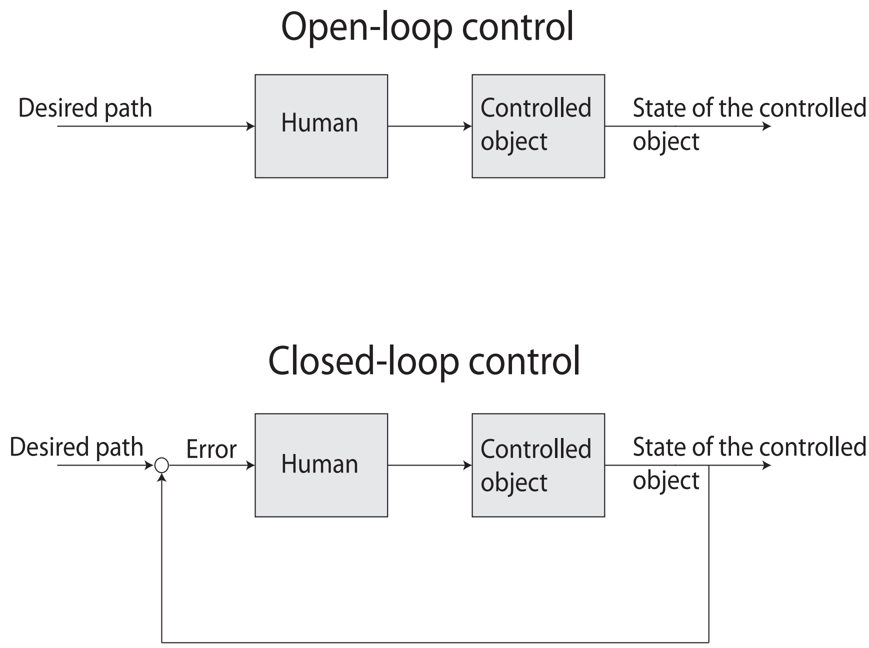

Figure 4: Open-loop (top) and closed-loop control models (bottom) of a visuomotor control task. In both cases, the human tries to follow a desired path, by controlling the controlled object.

control models consist of the same components. In the center of both is the human, who is involved in the visuomotor control task. The human receives a visual input about the desired path. In the case of driving a car, this could reflect the road heading. Based on this visual input, the human adapts the own behavior in order to pursue his or her goal, for example, to increase the pressure on the breaking paddle in order to slow down. This motor output is transmitted to the controlled object and results in a change of its state. This change in the state of the controlled object is, however, only perceived by the human, if we consider a closed-loop model (Figure 4, bottom). Only in this case will the changed state of the controlled object be fed back and, thus, can be included in the human's following motor output. In other words, while an open-loop model represents anticipatory behavior, where the impact of our own motor action is not observable, closed-loop models allow for compensatory behavior that specifically takes into account the consequences of one's previous action and to correct it, if necessary. These two models, and combinations of both, have been developed and validated by McRuer, with the purpose to model human behavior during flight (McRuer and Graham, 1965; McRuer et al., 1977; McRuer and Jex, 1967).

These models are specifically relevant for the current dissertation because they allow for deliberate manipulations of the task demand, in terms of mathematical functions. Such mathematical functions describe the desired path, or trajectory, to follow, which is also referred to as the forcing function of the visuomotor control task, as well as the control dynamics of the controlled object.

The forcing function can be formalized as a sum of sine waves that are non-harmonically related. Such a forcing function is perceived, by the participants, as random. We can increase the demands of the visuomotor control task, by increasing the bandwidth of the forcing function. This will result in a trajectory that contains faster and more frequent changes in direction. In the specific case of driving a car, this is comparable to a road with more and tighter curves.

The dynamics of the controlled object, formalized as a transfer function, describe the relationship between the input of the human to the controlled object and the output of the controlled object. For example, during driving, the transfer function of the vehicle would transfer the input from the driver, for example, the steering wheel angle, into an output state of the vehicle, for example, a heading direction.

We can increase the demands of the visuomotor control task, by increasing the order of the transfer function, for example from first to second order dynamics. This means that participants either control the velocity or the acceleration of the controlled object. As the latter requires to process higher derivations of the visual input signal it is considered to be more demanding (e.g., Wickens et al. (1984); Sirevaag et al. (1989)). Experimental validations have shown that both of these aspects, an increased bandwidth of the forcing function and an increase in the order of the transfer function, increase the task demands of the human in the loop. This increased demand was reflected in an increase in the perceived task demand (Scheer et al., 2016), a decrease of the visuomotor control performance (Kramer et al., 1983; Wickens et al., 1983, 1977; Scheer et al., 2016; Sirevaag et al., 1989) and a decrease in the ability to perform additional tasks (Isreal et al., 1980; Kida et al., 2004; Shulman and Briggs, 1971).

1.4.3 *Visuomotor control and the processing of unexpected auditory events*

The objective of the current dissertation is the processing of unexpected auditory events during visuomotor control. In Section 1.2 I described that visuomotor control demands can only decrease the ability to process auditory events, if both, the visuomotor control demands and the involuntary auditory processing, require the same type of attentional resources.

Interestingly, the two described manipulations of visuomotor control demands (i.e. increased bandwidth of the forcing function and an increase in the order of the transfer function) have been earlier shown to decrease different aspects of the processing of task-relevant auditory events. While both manipulations can decrease the ability of the participants to detect and respond to the target tones (Isreal et al., 1980), only the increased order of the transfer function decreased the amplitude of the P300 (Kramer et al., 1983; Wickens et al., 1983; Sirevaag et al., 1989), which is assumed to reflect the updating of the working memory with the target sounds (Donchin, 1981), while an increase in the bandwidth of the forcing function did not have a similar effect (Kramer et al., 1983; Isreal et al., 1980; Kida et al., 2004). This was taken as evidence that these two manipulations of visuomotor control demands consume different types of resources.

The series of experiments that established the relationship between visuomotor control demands and the processing of relevant auditory events is the basis for the experimental paradigm that I employed throughout the current dissertation. For this reason, I will describe it in some detail, in the following:

In this series of experiments, which was mostly conducted in the 1970s and 80s, the visuomotor control task was modelled as closed-loop control task. This visuomotor control task required the participants to continuously control a visually presented object. This controlled object was perturbed by random disturbances, which the participants were asked to compensate for. An example for such a task is illustrated in Figure 5 (left). The black line represents the controlled object, which is perturbed by random disturbances around the joint center of both lines, and the task of the participant is to counteract these disturbances and keep both lines as close to each other as possible, by manipulating a provided joystick. Besides the primary visuomotor task, participants

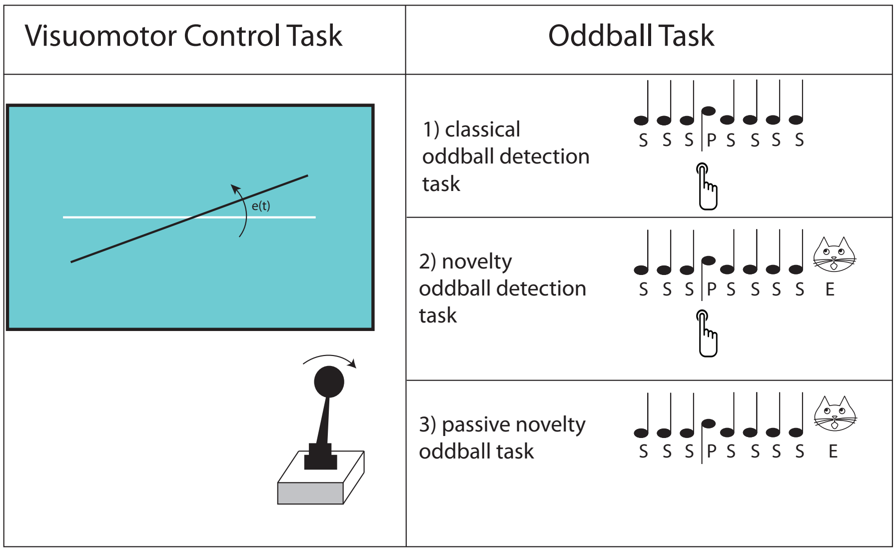

Figure 5: Left: Visuomotor control task, as visualized throughout the current dissertation. The black line rotates in quasi-random motions around the joint center of both lines. Participants are asked to minimize the error e(t) by rotating the joystick. Right: Different types of oddball detection tasks are shown. First, a classical oddball task, with frequent standard sounds ('S') intermixed with rare pure tones ('P'), which act as target and which the participants are asked to detect. Second, a novelty oddball task that is different from the classic oddball task in the sense that additionally to the rare pure tones, rare environment sounds ('E'), such as cat meows are presented. Third, a passive novelty oddball task that is similar to the novelty oddball task but does not require the participants to react to any of the rare pure tones.

listened to a series of auditory pure tones [1] that consisted of frequent standard and rare target tones, which differed from each other in pitch. The secondary task of the

[1] In the current dissertation, I use the term 'pure tones' in order to refer to beep tones. Such events have a constant amplitude and contain only one frequency. This contrasts with environment sounds, which were employed in the current dissertation, and that are complex in the sense that their amplitude changes over time and that they comprise a mixture of frequencies.

participants was to detect the target tones, for example by responding with a button press or by counting their number (see, Figure 5 (right, 1)). This type of task is often referred to as oddball task (Squires et al., 1975).

Grounded in multiple resource theory (see, Section 1.2), it was assumed that if primary and secondary task share the same limited attentional resources, an increase in visuomotor control demands would inevitably decrease the processing of the auditory target tones. In this series of experiments, the researchers were mostly interested in the aspect of auditory processing that is reflected in the amplitude of the P300 component (Kramer et al., 1983; Wickens et al., 1983; Sirevaag et al., 1989; Isreal et al., 1980; Kida et al., 2004). As the generation of the P300 was assumed to require perceptual-central resources, only such demands could impair its generation that also consumes perceptual-central resources. Demands which consume response-related resources, instead, would not have this effect. As an increase of the control dynamics' order, from velocity to acceleration control, reliably decreased the amplitude of P300, it was assumed that this type of demand requires perceptual-central resources (Kramer et al., 1983; Wickens et al., 1983; Sirevaag et al., 1989). This seems plausible, as the control of second order dynamics requires the participants to anticipate future velocities from the acceleration (i.e., the rate of velocity change). An increase in the bandwidth of the forcing function, which increases the number of direction changes of the rotating line, did not decrease the P300 (Kramer et al., 1983; Isreal et al., 1980; Kida et al., 2004). Isreal et al. (1980) suggested that this is due to the fact that this manipulation only consumes response-related resources, which are not required for the generation of the P300. Different than the increase in control dynamics' order, an increased number of random direction changes of the rotating line, requires more and faster motor responses but does not increase the demand for anticipating the future motion of the rotating line. This suggests that only some of the aspects that can increase visuomotor control demands decrease the perceptual-central processing of the relevant auditory events.

Whether and how the processing of unexpected and irrelevant auditory events is influenced by different control demands is investigated in Chapter 3 of the current dissertation.

1.4.4 *Summary*

In summary, the current section showed that visuomotor control requires the transformation of visual information into a motor output. On the neural level, this transformation is assumed to take place mostly in the dorsal stream but is supported by the perception of objects, in the ventral stream. Furthermore, visuomotor control can be modeled as a closed-loop control task. Within such a closed-loop task, the visuomotor control demands can be manipulated in a parametric way. Finally, earlier studies showed that only some of the visuomotor control demands impaired the cognitive processing of task-relevant auditory events.

1.5 THESIS OVERVIEW AND DISCUSSION

Imagine driving down a winding road, when suddenly the sound of a barking dog captures your attention. In this moment when the bark occurs, two opposing mechanisms will compete for your limited attentional resources. On the one hand, the involuntary urge to orient your attentional resources towards the unexpected and salient auditory event. On the other hand, the necessity to voluntarily focus these attentional resources on the visuomotor control of the car. Given that both, involuntary and voluntary attention control mechanisms, are likely to rely on the same limited attentional resources, they might interfere with each other. It is possible that the involuntary allocation of attentional resources to the barking dog distracts your ability to follow the road. Alternatively, you might not become aware of the barking dog, because your attentional resources are fully allocated to the road ahead. But which factors define whether you will orient your attentional resources towards the barking dog and will this, indeed, decrease your driving performance?

The current dissertation summarizes a series of visuomotor control experiments, concerned with these questions. For this purpose, I address two main topics that are summarized in the two parts of the following discussion. First, I will discuss whether and how the properties of the auditory distractor sounds define their involuntary processing. Second, I will discuss whether and how the voluntary attention control mechanism influences human distractibility, for example when task demands increase.

1.5.1 *Properties of the unexpected auditory events*

The first part of my dissertation consists of Chapter 2 and the appendix in Chapter 5.1. In these chapters, we identified two factors that influence the involuntary attentional processing of irrelevant and unexpected auditory events: First, how different the event is from the auditory context that it is presented in and, second, the familiarity of the event. I use the remainder of this section, to describe our conducted experiments and to elaborate on the relevance of our findings.

It has been consistently shown that the brain responds strongly to unexpected auditory events, even when they are of no relevance for the currently performed task (e.g. Parmentier et al. (2008); Bidet-Caulet et al. (2015); Hughes et al. (2007) and for a review: Parmentier (2014)). Common examples for such unexpected events are rare tones (i.e. deviants) in passive oddball tasks (see, Figure 5, left 3), which are unexpected given their low probability of occurrence. In such oddball tasks, rare auditory events are processed significantly more than the frequent standard tones. This enhanced processing results in the characteristic distraction potential, of the ERP (see, Section 1.3), and can hamper the performance in concurrently performed tasks (Allison and Polich, 2008; SanMiguel et al., 2008; Cycowicz and Friedman, 1998; Debener et al., 2005; Friedman et al., 2009).

environment sound and pure tone distractors Two types of infrequent auditory events, or distractors, have been frequently employed to study how these unexpected sounds, involuntarily, control attentional resources. First, rare pure tones that deviate from the frequent pure tones in pitch or loudness (Allison and Polich, 2008; Squires et al., 1975) and second, rare environment sounds (SanMiguel et al., 2008; Cycowicz and Friedman, 1998; Debener et al., 2005; Friedman et al., 2009). It is generally unclear whether and how the choice of using either a pure tone distractor or environment sound distractor would influence the outcome of these studies.

In Chapter 2, we show that the choice of the distractor can, indeed, have a significant influence on the strength of involuntary distraction as well as on its interaction with a concurrently performed task. We show that rare environment sounds resulted in significantly larger brain responses (i.e. ERPs) than rare pure tones in a passive oddball task (see, Figure 5, left 3). The generation of larger ERP amplitudes is typically interpreted to reflect increased processing of the eliciting event (e.g. Polich (2007); Luck (2005)). Taking this into account, our ERP results suggest that environment sounds were processed more than the pure tones. Interestingly, especially the ERP components novelty-P3 and RON, of the distraction potential, were enhanced for the environment sounds. The distraction potential is claimed to represent neural components that underlie how we detect unexpected events (i.e., MMN/N1), orient our attentional resources to this event (i.e., novelty-P3), and re-orient the resources back to the task at hand (i.e. RON) (Escera and Corral (2003); Wetzel and Schröger (2014); Escera and Corral (2007); Horváth et al. (2008) and see, Section 1.3). Based on this model, the environment sounds especially increased the allocation of attentional resources to the distractor sound, relative to pure tones. This, in turn, also increased the necessity to reorient resources away from the distractors, after their processing. As these steps have been earlier shown to consume attentional resources (SanMiguel et al., 2008; Wetzel and Schröger, 2014; Escera and Corral, 2007), we suggest that the processing of the environment sounds consumes more attentional resources than the processing of the pure tones. Thus, we could show that the choice of the distractor (i.e. environment sound or pure tone) influences involuntary attention control.

Interestingly, the choice of distractor sound did not only influence the involuntary processing of the distractors itself but also their interaction with the voluntarily performed task. The introduction of a concurrent task (i.e., visuomotor control) resulted in a significant decrement of the ERP amplitudes that were elicited by the environment sounds, relative to a passive viewing condition. In contrast, this was not the case for the task-irrelevant pure tones, which elicited comparable ERPs whether or not there was a need to perform a visuomotor control task. More specifically, the introduction of a visuomotor control task decreased the amplitude of novelty-P3 and RON, but not MMN, of the distraction potential, which was elicited by the environment sounds. This suggests that the visuomotor control demands do not decrease the ability of our participants to detect unexpected environment sounds, but decreased their attentional orientation to and away from the environment sound. Thus, environment sounds are more likely to create a resource conflict with a concurrently performed task, possibly because they consume significantly more attentional resources than the rare pure tones. This is supported by the observation that specifically those ERP components were decreased by the visuomotor control task that were shown to be enhanced for the environment, relative to the pure tone, distractors.

Thus, in order to study how unexpected sounds control attentional resources, it seems to be advantageous to use environment sounds, instead of pure tones, as distractors, because the former consume more attentional resources and are more likely to provoke a resource conflict with a concurrently performed task.

THE FAMILIARITY OF THE ENVIRONMENT SOUNDS It is interesting to note that the two types of distractors, environment sounds, and pure tones, were processed differently, although both of them were equally unexpected in the sense of their probability of occurrence. This shows that the probability of occurrence of an auditory event is only one aspect that influences its involuntary processing. Which other factors could account for our observed differences between environment sounds and pure tones?

It has been claimed that conflicts between an auditory event and our expectations determine the extent to which the unexpected event is involuntarily processed. In other words, the more different an auditory event is from our expectations of the environment, which are believed to be generated by a predictive model, the more likely it is that the brain will involuntarily attend to process such events, so as to update our expectations (see, Schröger et al. (2015a,b) and Section 1.3). The predictive model, against which the auditory events are compared, was suggested to include the short-term local context, as well as long-term memory representations, of the auditory events (Schröger et al., 2015a). In the presented study, the short-term context in which both types of distractors were presented, were the frequent pure tones. Arguably, environmental distractors that are a complex combination of multiple frequencies are more dissimilar to this context than pure tone distractors. This could have caused environmental sounds to have involuntarily recruited more attentional resources than the pure tones. If environment sounds recruit more attentional resources, it is also more likely that they compete for attentional resources with a concurrently performed task.

Sound familiarity is another aspect of environment sounds (e.g., dogs, cats, babies) that could account for its high demand for attentional resources. Events that are highly familiar and personal meaningful, such as one's own name (Tacikowski et al., 2014) or a familiar voice (Holeckova et al., 2006) are processed preferentially, relative to unfamiliar events, presumably because their long-term memory representation facilitates their processing (Schröger et al., 2015a). However, it is less established whether environment sounds, which are familiar but not personally meaningful, have the same effect.

In summary, environment sounds could be preferentially processed because they are more different from the context or highly familiar or both.

In the appendix in Chapter 5.1, we suggest that it is not the familiarity of the environment sounds that results in their preferential processing. Indeed, familiar sounds attracted less attentional resources than their unfamiliar counterpart, which we matched for their difference from the context. Earlier studies suggested that this difference in processing, between familiar and unfamiliar environment events, becomes even more apparent with repetition. Both ERP (Friedman et al., 2001) and functional magnetic resonance imaging (fMRI) (Henson, 2000) studies showed, that while the repetition of unfamiliar sounds increases their processing, repeated familiar sounds are processed less and less. Overall, this leads to an increased difference in processing between familiar and unfamiliar sounds. The authors of these studies assume that the increased processing of the unfamiliar sounds reflects the generation of a memory template for the unfamiliar sounds, while the decreased processing of the familiar sounds reflected gradual adaptation to a template that already existed.

Thus, different than familiar and personal meaningful events, such as the own name, familiar environment sounds are not preferentially processed. This suggests that a different factor should be responsible for the measured difference between the environment sounds and the pure tones in the study, reported in Chapter 2. I argue that environment sounds are preferentially processed, primarily because of their difference from the context, as was described earlier in this section. Indeed, an increase in the difference of an auditory event to its context was shown to have similar effects as we observed for the comparison between environment and pure tones (Berti et al., 2004). Berti et al. (2004) parametrically increased the difference of the distracting auditory event from its context, by increasing the pitch difference between both. Like we reported for the environment sounds, such an increase in pitch difference resulted in an increase in novelty-P3 and RON and an increased competition for attentional resources with a concurrently performed auditory discrimination task.

In summary, the properties of the unexpected auditory event can have a major influence on its involuntary processing and the competition for attentional resources with a concurrently performed task. In particular, it is an environment sound's dissimilarity from its context that determines the extent to which attentional resources are involuntarily allocated for its processing. Such highly different events contain information, which might not be of direct relevance for the performance of our current task. Nonetheless, it is necessary in order to update one's predictive model of the environment and, in doing so, maintain situation awareness and respond to novel threats (see Section 1.3).

These results also have practical implications for the design of warning sounds. Our results suggest that the most important factor that increases the probability that an unexpected warning sound triggers attentional processing is its difference from the context, instead of intrinsic factors, such as the loudness. Furthermore, while loud sounds are known to elicit a startle response (e.g. Ramirez-Moreno and Sejnowski (2012)), an unconscious defensive response that can disrupt the current task, our results suggests that sounds that are highly different from their context, such as environment sounds, are processed preferentially but do not interrupt the concurrently performed task.

1.5.2 *The influence of voluntary attention control on auditory distraction*

In the previous section, I discussed two properties of unexpected auditory events that influences their involuntary processing and, in turn, their competition for attentional resources with a concurrent task (i.e., visuomotor control). In the current section, I will establish that the involuntary processing of unexpected auditory events can also depend on the voluntary intentions of the observer. More specifically, I show that both, the demands for attentional resources in the visuomotor control task, as well as the relevance of the auditory modality, have an impact on the involuntary processing of unexpected auditory events. I use the remainder of this section to describe our conducted experiments and to elaborate on the relevance of our findings.

The influence of increased task demands on the involuntary processing of the auditory events

In the previous section, I established that voluntary and involuntary attention control compete for the same attentional resources and thus can interact. This corresponds with everyday experiences and experimental evidence that show, for example, that the involuntary processing of an unexpected auditory event can occasionally hamper our ability to voluntarily maintain stable performance in a concurrently performed task (e.g. SanMiguel et al. (2008); Parmentier et al. (2008); Berti (2008); Schröger and Wolff (1998b); Parmentier (2014); Schröger et al. (2000)). But is this interference only driven by exogenous factors, such as the properties of the unexpected auditory event described in the previous section, or is it subject to our voluntary intentions?

By definition, the involuntary allocation of attention is not under our direct intentional control (Reber, 1985). Even if we were under explicit instructions to ignore all auditory events, the brain will nevertheless respond to auditory distractors and devote some attentional resources to process it (Parmentier et al., 2008; Lepistö et al., 2004; Alho et al., 1998; Daffner et al., 2003; Wetzel et al., 2013; Escera and Corral, 2007; Eimer et al., 1996; Escera and Corral, 2003; Parmentier, 2014). We could take these results as evidence, that the interference between voluntary and involuntary attention control is not subject to our voluntary intentions.

However, in Chapter 3 we show that this is not entirely correct. Although we cannot intentionally inhibit involuntary attention control, the demands in a voluntarily performed task can nevertheless decrease its impact. More specifically, when we increased the demands in the visuomotor control task, the measured brain responses to task-irrelevant and unexpected environment sounds decreased. Thus, the balance between our voluntary and involuntary attention control mechanisms can be adjusted to our current demands. This cannot be explained readily with the limitation of attentional resources but additionally suggests a supervisory system that reduces, under high load, the amount of attentional resources that can be involuntarily captured.

Such a supervisory system has been conceptualized within the theoretical framework of the working memory system (Knudsen, 2007). Within this framework, it is assumed that the central executive of the working memory system determines which information we voluntarily attend to. Task-relevant stimuli are enhanced for cognitive processing while task-irrelevant stimuli are diminished. In combination, these mechanisms result in an overall enhancement of the processing of relevant stimuli, relative to those that are irrelevant (Hofmann et al., 2012; Munakata et al., 2011). This mechanism of enhancing relevant and diminishing irrelevant information processing could also be responsible for the adjustment of the balance between voluntary and involuntary attention control under load. When task demands increase, more resources are needed to satisfy these demands. Thus, the processing of relevant stimuli is increased. Importantly this also further diminishes the processing of any information that is not relevant and could, in doing so, reduce the processing of unexpected events, such as environment sounds (Boudreau et al., 2006; Knudsen, 2007). Thus, the diminished processing of an unexpected event that accompanies increased task demands, could be a byproduct of the increased processing of the task-relevant information.

DISTINGUISHING BETWEEN DIFFERENT TYPES OF DEMANDED RESOURCES It has already been mentioned (see, Section 1.2), that different resources are required for different aspects of any given task (Wickens, 1980, 2002). In the context of visuomotor control, there are at least two broad classes of resources, that should be distinguished, namely: (i) response-related, and (ii) perceptual-central resources. As described in Section 1.4, response-related resources are required to cope with faster and more frequent directional reversals of the controlled object, while perceptual-central resources are required to deal with higher order control dynamics (Kok, 2001).

Interestingly, in Chapter 3 we show that only perceptual-central, but not response-related, demands diminish the measured brain responses (i.e. ERPs) to the unexpected environment sounds. This means that perceptual-central, but not response-related, resources are required for the processing of the environment sounds, which is the basis for the generation of the ERPs. More importantly, this is specific to one component of the ERP, namely the late novelty-P3. To reiterate, while visuomotor control diminishes early and late novelty-P3s, and RON (see results of Chapters 2, 3, 4 and 5.1), only the late novelty-P3 responds to manipulations of perceptual-central resource availability.

Previous work have shown that similar to this late novelty-P3, also the P300 to target tones, is diminished when the visuomotor control task increases in its demands for perceptual-central resources (Kramer et al., 1983; Wickens et al., 1983; Sirevaag et al., 1989), but not response-related resources (Kramer et al., 1983; Isreal et al., 1980; Kida et al., 2004) (see also Section 1.4). This noted similarity between P300, which is suggested to reflect context updating, and the late component of novelty-P3 can help us to clarify how the attentional processing of unexpected environment sounds is hampered by the increased perceptual-central visuomotor control demands.

The late novelty-P3 is part of the distraction potential (see, Section 1.3). This distraction potential is claimed to represent neural components that underlie how we detect unexpected events (i.e., MMN/N1), orient our attentional resources to these events (i.e., novelty-P3), and re-orient the resources back to the task at hand (i.e. RON) (Escera and Corral, 2003; Wetzel and Schröger, 2014; Escera and Corral, 2007; Horváth et al., 2008). As late novelty-P3 is a subcomponent of novelty-P3, we could interpret its attenuation by high perceptual-central load as reflecting the decreased orientation of attentional resources to the unexpected environment sound. However, this interpretation disregards the fact that we only find one, and not both, subcomponents of novelty-P3 decreased. Differences between early and late novelty-P3 have been already reported in earlier studies that showed that both subcomponents of novelty-P3 were influenced in different ways by experimental manipulations (Cycowicz and Friedman, 1998; Gaeta et al., 2003; Strobel et al., 2008; SanMiguel et al., 2008) and were associated with different neural origins (Debener et al., 2005; Yago et al., 2003). Summarizing these studies, early novelty-P3 might reflect attention orienting to unexpected events, because it is sensitive to the dissimilarity of an event from its context (Gaeta et al., 2003; Strobel et al., 2008) and shows a reduction in amplitude with stimulus repetition (Cycowicz and Friedman, 1998). Late novelty-P3, however, might be similar to P300 and thus reflect the context updating in the working memory, because it is sensitive to the event's relevance (Gaeta et al., 2003; Strobel et al., 2008) and the necessity to generate a working memory template for unknown events (Cycowicz and Friedman, 1998).

If this is considered to be correct, our results suggest that an increase in perceptual-central demands does not decrease the orientation of attentional resources to the unexpected auditory event but instead decreases the likelihood that such an event updates the working memory content. This updating of the working memory is necessary, in the first place, in order to update our predictive model of the environment. As this predictive model ensures situational awareness, this would suggest that the increased protection from auditory distraction, during high perceptual-central load, comes with the cost of a decreased awareness of our auditory environment.

DEMANDS IN THE CONTINUOUS VISUOMOTOR CONTROL TASK IN COMPARISON TO PREVIOUS RELATED WORK There is a notable difference between the experiments reported in this dissertation and previous related work, which similarly investigated how changes in primary task demands influence how the brain responds to unexpected and task-irrelevant auditory events. For example, SanMiguel et al. (2008) showed that increasing the difficulty in an n-back task, diminished late novelty-P3 even when the auditory modality was ignored. In contrast, I only found diminished late novelty-P3s when the auditory modality was explicitly attended to (see, Chapter 3), and not when the auditory modality was explicitly ignored (see, Chapter 2). Why does this difference exist? I propose that this could be accounted for in three ways that are not mutually exclusive. First, it is possible that our manipulation of task demands did not decrease the availability of attentional resources sufficiently, so as to diminish the involuntary attentional processing of the unexpected auditory events, in cases in which the auditory modality was to be ignored. However, the performance in the visuomotor control task contradicts this explanation. For all our participants, increasing visuomotor control demands consistently decreased their performance. Furthermore, some of our participants were barely able to maintain a stable control in the more demanding condition.

Second, it is possible that our manipulation of task demands did not decrease the type of attentional resources that was required for the involuntary attentional processing of the unexpected auditory events. Although we, like previous related work, manipulated perceptual-central resources, it is possible that different types of perceptual-central resources exist. Indeed, it has been suggested that multiple resource theory is incomplete in the sense that it does not account for all types of attentional resources (Boles and Law, 1998; Boles, 1996). However, if this was the case, increasing the visuomotor control demands should never influence the extent of involuntary distraction. The findings, presented in Chapter 3 show that this is not true. When participants were instructed to attend to the auditory modality, increasing visuomotor control demands decreased the extent of involuntary distraction by environment sounds.

Third, the fact that in a visuomotor control task, but not in previous related work, the task-relevant visual information is subject to continuous change, could have hampered the orientation of attentional resources to the unexpected auditory events. In a continuous task, such as the visuomotor control task, participants focus their attentional resources continuously on the task. For this reason, it was suggested that in continuous tasks it is less likely that attentional resources are oriented towards unexpected auditory events, than in a task whereby relevant information is presented at discrete points in time (Lachter et al., 2004; Muller-Gass et al., 2007). This could account for the difference between the current dissertation and previous work. In cases in which the auditory modality was explicitly ignored (see, Chapter 2), it is plausible that participants focused their attentional resources continuously on the visuomotor control task. Thus, it is less likely that attentional resources slip away for the processing of additional events than it would be in a discrete task. Based on this, we can assume that during the performance of a continuous task, the unexpected auditory events should be processed mainly automatically (i.e. without requiring attentional resources). For this reason, a further decrease in the availability of attentional resources, due to the increase in task demands, would not hamper this automatic processing of the unexpected auditory events, similar as it was shown in Chapter 2 of the current dissertation. However, when the auditory modality is relevant, as it was the case in Chapter 3 of the current dissertation, participants have to spend attentional resources for the processing of the relevant auditory events. Thus, attentional resources are no longer continuously focused on the visuomotor control task and can slip away for the processing of unexpected events. In turn, a decrease in their availability can decrease the processing of the unexpected auditory events, similar as it was shown in Chapter 3. If this third option is correct, future research could employ a discrete, instead of a continuous, visuomotor control task. This would increase the likelihood that attentional resources are distracted away by unexpected auditory events, even if the auditory modality is explicitly ignored. Such a discrete visuomotor control task would be the step tracking task, in which the visual input is changing in discrete steps, which the participants have to compensate for with a control device (Kramer and Strayer, 1988; Sirevaag et al., 1989; Wickens et al., 1983).

Future research can investigate whether indeed the third account is valid, given that a better understanding would enable researchers to systematically manipulate visuomotor control demands in a way that diminishes the brain's responses to unexpected auditory events even when the auditory channel is explicitly ignored.

Increased voluntary allocation of attentional resources to the auditory modality

In the previous section, I showed that the involuntary processing of unexpected auditory events decreases with increasing visuomotor control demands. This was attributed to the reduced capacity of attentional resources, which are shared between the visuomotor control task and the auditory processing (c.f. Dehais et al. (2016); Molloy et al. (2015); Dehais et al. (2014); Causse et al. (2016); Giraudet et al. (2015)). In the most extreme case, such a reduced capacity of attentional resources, during high visual load, has been reported to induce inattentional deafness, which is the neglect of auditory stimuli, due to a lack of available attentional resources (Macdonald and Lavie, 2011; Raveh and Lavie, 2015). However, the amount of attentional resources that is allocated to the processing of unexpected auditory events might not solely depend on the load of the main task. Indeed, in a flight simulator study, Dehais and colleagues reported two independent factors that influenced the processing of unexpected auditory events (Dehais et al., 2014): Task demands and perceived relevance of the auditory modality.

As expected, Dehais et al. (2014) showed, that the demands in a simulated flight task significantly decreased the pilots' ability to detect the unexpected auditory events, which were task-relevant alarms. During the execution of a highly demanding visuomotor flight maneuver, 11 out of the 28 highly-trained pilots failed to notice the auditory alarm for landing gear failure. Similar, as in Chapter 3 of the current dissertation, this failure was attributed to the reduced capacity of attentional resources that are shared between auditory and visual modality, caused by high demands in the visuomotor flight task. Interestingly, the authors reported that the pilots no longer neglected the auditory alarms after they had experienced these alarms once. This was the case even when the pilots experienced high visual load and, thus, should not have the capacity to process the auditory alarms. This suggests that the processing of unexpected auditory events does not depend solely on the extent to which attentional resources are depleted by the visuomotor control task but, additionally, depends on the perceived relevance of the auditory modality.

Despite these results, the neglect, or attenuation, of unexpected auditory events in the presence of a demanding task is still mostly attributed to the reduced capacity of cross-modal attentional resources, that are shared between visual and auditory modality (Macdonald and Lavie, 2011; Molloy et al., 2015; Raveh and Lavie, 2015; Dehais et al., 2016; Giraudet et al., 2015).

In Chapter 4 we provide evidence that, as suggested in the study by Dehais et al. (2014), the relevance of the auditory modality increases the processing of the unexpected auditory events.

Those of our participants, for whom the auditory modality was relevant, processed the unexpected and task-irrelevant environment sounds substantially more than those participants that we instructed about the irrelevance of the auditory modality. This suggests that when the auditory modality is relevant, more attentional resources are available for the processing of unexpected auditory events, even though these events, themselves, are irrelevant. Importantly, this increased availability of attentional resources for auditory processing was not at the expense of the, concurrently performed, visuomotor control task. Neither was the visuomotor control performance impaired by the auditory relevance nor did visuomotor control demands and auditory relevance interact in their effect on the processing of the unexpected environment sounds. This is important because it suggests that the relevance of the auditory modality did not withdraw attentional resources from the visuomotor control task. Instead, it suggests that auditory relevance increases the availability of attentional resources that are specific to the auditory modality (c.f. Keitel et al. (2013); Talsma et al. (2006); Keitel et al. (2013)). It is interesting to note, that the relevance of the auditory modality specifically influenced the late subcomponent of novelty-P3. In Chapter 3 we reported the same ERP component to be compromised by increased demands for perceptual-central resources in the visuomotor control task. This suggests that high visuomotor control demands and auditory relevance have an impact on the same stage of the three-staged distraction model, namely the updating of the predictive model of the environment with the unexpected event and, thus, situational awareness.

This suggests that in cases in which task demands are high and situational awareness is at a risk, an increase in auditory relevance could counteract this detrimental effect. Importantly, as auditory relevance enhances the availability of modality-specific resources, this would not put the performance of the main task at a risk.

In summary, we suggest that the involuntary control of attention, in the current dissertation manifested in the processing of unexpected and irrelevant auditory events, is not fully independent of its voluntary counterpart. We showed two cases in which the involuntary attentional processing was depended on the voluntary intentions of our participants. First, high visuomotor control demands can bias attentional resources, which are shared between auditory and visual modality, towards the demanding visual task. This leaves less attentional resources for the involuntary processing of unexpected auditory events. Second, the relevance of the auditory modality can increase the availability of modality-specific attentional resources and, thus, increases the involuntary processing of unexpected auditory events, independent of the demands of the visuomotor control task.

1.6 DECLARATION OF CONTRIBUTION

This dissertation comprises a collection of manuscripts that are either published or presented for publication. Details about these manuscripts are presented in the following. The ideas for the studies, their experimental design and software were developed by the candidate. The data collection and analysis was performed by the candidate. The co-authors, Lewis L. Chuang and Heinrich H. Bülthoff supervised the work of the candidate and assisted in the revision of the manuscripts.

- Scheer, M., Bülthoff, H. H., Chuang, L. L. (2016). Steering demands diminish the early-P3, late-P3 and RON components of the event-related potential of task-irrelevant environmental sounds. *Frontiers in Human Neuroscience*, 10, 1-15.

- Scheer, M., Bülthoff, H. H., Chuang, L. L. (2017). Auditory task irrelevance: A basis for inattentional deafness (submitted).

- Scheer, M., Bülthoff, H. H., Chuang, L. L. (2017). Late novelty-P3 to irrelevant environmental sounds and P3b to relevant auditory targets are selectively diminished by perceptual-central demands of continuous visuomotor control (submitted).

Parts of this work were also presented at the following conferences:

- Scheer M., Bülthoff H. H. and Chuang L. L. (2014) Is the novelty-P3 suitable for indexing mental workload in steering tasks?, *12th Biannual Conference of the German Cognitive Science Society*, Springer, Berlin, Germany, Cognitive Processing, 15(Supplement 1), S135-S137.

- Scheer M., Nieuwenhuizen F. M., Bülthoff H. H. and Chuang L. L. (2014) The Influence of Visualization on Control Performance in a Flight Simulator In: Engineering Psychology and Cognitive Ergonomics, *11th International Conference on Engineering Psychology and Cognitive Ergonomics*, held as Part of HCI International 2014, Springer, Berlin, Germany, 202-211, Series: Lecture Notes in Artificial Intelligence ; 8532.

- Chuang L. L., Flad N., Scheer M., Nieuwenhuizen F. M. and Bülthoff H. H. (2014) Abstract Talk: Closed-loop control performance and workload in a flight simulator, *56th Conference of Experimental Psychologists* , Giessen, Germany 45.

- Scheer M., Bülthoff H. H. and Chuang L. L. (2015): On the influence of steering on the orienting response In: Trends in Neuroergonomics, *11. Berliner Werkstatt Mensch-Maschine-Systeme*, Universittsverlag der TU Berlin, Berlin, Germany, 24.

- Scheer M., Bülthoff H. H. and Chuang L. L. (2015) On the Cognitive Demands of Different Controller Dynamics: A within-subject P300 Analysis, *Human Factors and Ergonomics Society Annual Meeting*, Sage, London, UK, 1042-1046.

- Scheer M., Bülthoff H. H. and Chuang L. L. (2015): Measuring workload during steering: A novelty-P3 study, *57th Conference of Experimental Psychologists (TeaP 2015)*, Hildesheim, Germany.

- Scheer M. (2016) Abstract Talk: Attending to the Auditory Scene Improves Situational Awareness, *1st Neuroergonomics Conference*: The Brain at Work and in Everyday Life, Paris, France.

- Chuang L. L. and Scheer M. (2016) Abstract Talk: Evaluating steering demands from EEG/ERP responses to task-irrelevant distraction, *50. Kongress der Deutschen Gesellschaft fr Psychologie (DGPs 2016)*, Leipzig, Germany 49.

2

AUDITORY DISTRACTION BY PURE TONE AND ENVIRONMENT DISTRACTORS

This chapter has been reproduced from an article published in Frontiers in Human Neuroscience: Scheer, M., Bülthoff, H. H., Chuang, L. L. (2016). Steering demands diminish the early-P3, late-P3 and RON components of the event-related potential of task-irrelevant environmental sounds. *Frontiers in Human Neuroscience*, 10, 1-15.

2.1 ABSTRACT

The current study investigates the demands that steering places on mental resources. Instead of a conventional dual-task paradigm, participants of this study were only required to perform a steering task while task-irrelevant auditory distractor probes (environmental sounds and beep tones) were intermittently presented. The event-related potentials (ERPs), which were generated by these probes, were analyzed for their sensitivity to the steering tasks demands. The steering task required participants to counteract unpredictable roll disturbances and difficulty was manipulated either by adjusting the bandwidth of the roll disturbance or by varying the complexity of the control dynamics. A mass univariate analysis revealed that steering selectively diminishes the amplitudes of early P3, late P3, and the re-orientation negativity (RON) to task-irrelevant environmental sounds but not to beep tones. Our findings are in line with a three-stage distraction model, which interprets these ERPs to reflect the post-sensory detection of the task-irrelevant stimulus, engagement, and re-orientation back to the steering task. This interpretation is consistent with our manipulations for steering difficulty. More participants showed diminished amplitudes for these ERPs in the hard steering condition relative to the easy condition. To sum up, the current work identifies the spatiotemporal ERP components of task-irrelevant auditory probes that are sensitive to steering demands on mental resources. This provides a non-intrusive method for evaluating mental workload in novel steering environments.

2.2 INTRODUCTION

Safety concerns have strongly motivated research in determining the demands, or workload, that users experience while performing closed-loop steering tasks, particular in the context of driving a car or piloting an aircraft (for a general review about workload, see (Kramer, 1991; Wickens, 2008; Young et al., 2015)). Even if competence can be maintained in spite of high mental workload, such scenarios leave little spare capacity for handling unexpected occurrences. There is no doubt that steering places high requirements on visual and motoric resources (Land and Lee, 1994; Salvucci and Gray, 2004). Besides this, some aspects of steering have also been shown to require mental resources (Wickens et al., 1984, 1983). This has been typically demonstrated with the use of dual-task paradigms that induce a competition for mental resources between the primary steering task and an appropriately chosen secondary task (Mcleod, 1977; Wickens and Gopher, 1977). The purpose of this paper is to evaluate the demands that steering places on mental resources without requiring the user to perform a secondary task. To do so, we investigate how steering demands modify the event-related potentials (ERPs) to task-irrelevant auditory probes. The steering task is further manipulated for two aspects of steering that are known to influence handling difficulty, namely the bandwidth of disturbance and the complexity of (vehicle) control dynamics.

Workload can be defined as the ratio between the demands of a task and the resources of the human operator (Kantowitz, 1987; O'Donnell and Eggemeier, 1986). Its concept originates from the idea that human operators possess, at any given time, a limited reserve of mental resources (Kramer, 1991; Wickens, 2008). By introducing a competition for this limited reserve, for example by requiring participants to perform two tasks simultaneously, researchers are able to investigate how difficulty manipulations in a primary task can create a demand for resources that are drawn away from an accompanying secondary task. Changes in resource demands are indexed by secondary task performance. A comparison of performance measures on competing tasks typically demonstrate that participants are capable of varying the relative prioritization of competing tasks (Wickens and Gopher, 1977), but only when the tasks overlap in their resource requirements (Mcleod, 1977). The Multiple Resource Theory provides a framework that allows researchers and practitioners to define the resource requirements of different tasks and, in doing so, predict possible conflicts (Wickens and Yeh, 1983; Wickens, 2008, 2002). Within this framework, a steering task places obvious demands on visual perception and motoric responses. By using electroencephalography (EEG) to measure the event-related potentials (ERP) to secondary task stimuli, Wickens and colleagues were able to demonstrate the demands of various aspects of steering on mental resources as well.

To date, ERP studies have broadly demonstrated that steering demands tend to reduce the amplitude of the P300, an ERP component that is generated by the target stimuli of a secondary task (e.g. (Isreal et al., 1980; Wickens et al., 1977, 1983)). Dual-task studies that investigate steering demands typically require participants to detect and explicitly respond to infrequently presented oddball targets as a secondary task. Oddballs elicit a prominent P300 component in the EEG signal. The P300 is a positive deflection between 250 and 400 ms and its amplitude has been used to index the level of experienced workload (Kok, 1997). The finding that steering demands diminish P300 amplitudes in an accompanying oddball detection task is commonly interpreted as follows. The primary steering task places prioritized demands on mental resources, resulting in the reduced availability of mental resources that would otherwise be recruited for the detection of secondary oddball targets (Isreal et al., 1980; Wickens et al., 1977, 1983). Hence, the reduced availability of mental resources is reflected in the reduced amplitudes of P300 that are elicited by the detected oddballs. This serves as a proxy for evaluating the demands for mental resources, given different manipulations of steering difficulty. Some steering parameters exert a uniform cost on P300 amplitudes regardless of their manipulated difficulty levels, while increasing the difficulty levels of other parameters can induce decreased P300s to secondary oddball targets. For example, increasing the number of simultaneously tracked dimensions (Kramer et al., 1983; Sirevaag et al., 1989; Wickens et al., 1977), tracking speed (Kida et al., 2004), and the frequency bandwidth of the tracked target (Isreal et al., 1980) do not result in a decrease of P300 amplitudes. In contrast, increasing the complexity of control dynamics (e.g., from a first-order to a second-order integrator; (Sirevaag et al., 1989; Wickens et al., 1984, 1983)) or the unpredictability of the tracked target (Kida et al., 2004) result in corresponding decreases in

P300 amplitudes. Other ERP components have also been analyzed for their sensitivity to changes in steering demands, albeit with mixed results. (Kida et al., 2004) reported a decrease in the amplitude of the N140 component to the somatosensory targets of a secondary oddball task, which did not vary with the predictability of the steering task. To date, ERP studies of steering demands have mainly been performed in the presence of a secondary task that contains the stimuli for eliciting the ERP. It is generally believed that ERP probes are only effective for evaluating the resource demands of tasks that they are in explicit conflict with. Indeed, (Wickens et al., 1983) have shown that the influence of steering demands on P300 amplitudes is removed when the ERP probes were task-irrelevant. Unfortunately, dual-task paradigms present several limitations in understanding steering demands. First, requiring an overt response to a secondary task interferes with the performance of the primary steering task (Wickens et al., 1983). In this regard, the secondary task is not a passive consumer of residual mental resources but is, rather, in direct competition with the primary task for shared resources. Second, the researcher has little control over how participants might choose to divide their resources between primary and secondary task, regardless of explicit instructions. Finally, estimated workload from ERP measurements could be due to the interaction of the primary and the secondary task demands, instead of the primary task alone. These reasons, amongst others, have motivated the development of non-intrusive methods for estimating primary task demands that do not necessitate a secondary task.

In contrast to (Wickens et al., 1983) findings, ERPs to task-irrelevant stimuli can sometimes be demonstrated to vary with the demands of a task that is performed in isolation. This has been shown with the use of ERP probe stimuli that are more likely to recruit larger momentary shifts of resources than simple beep tones, such as complex environmental sounds (Courchesne et al., 1975; Polich, 2003; Ullsperger et al., 2001). Such stimuli are task-irrelevant and reliably elicit a positive ERP component termed the novelty-P3 (P3a) that has a similar time-course to the P300 but with a frontal instead of a parietal distribution (Polich, 2007). Given their task-irrelevant nature, it is more reasonable to assume that their elicited ERP components reflect residual resources that are not consumed by the demands of the investigated task. Task-irrelevant probes have been used to estimate the demands of a variety of tasks including arithmetic and visual monitoring (Ullsperger et al., 2001), working memory task (i.e., n-back task; (SanMiguel et al., 2008)), Tetris (Dyke et al., 2015; Miller et al., 2011), first-person-shooter (Allison and Polich, 2008) and car racing games (Burns and Fairclough, 2015). It has not always been necessary to employ novel environmental sounds in order to generate ERPs for the evaluation of task demandssimple beep tones have proven to be sufficient in some instances (Burns and Fairclough, 2015). Nonetheless, there are also other examples whereby simple beep tones do not generate ERPs (i.e., P3a) that are sensitive to task demands (e.g. (Muller-Gass et al., 2007; Ullsperger et al., 2001)). Environmental sounds have the added value of generating larger novelty-P3s that are further separable for an early and late P3 component, which are claimed to be functionally distinct (Alho et al., 1998; McDonald et al., 2010; Yago et al., 2003). Early P3 is claimed to reflect post-sensory detection of unexpected events that contradict the observers representation of the external world, while late P3 is claimed to reflect attentional processing of the unexpected event. Besides novelty-P3, other ERP components of task-irrelevant probes (i.e., N1/MMN (Dyke et al., 2015) (Ullsperger et al., 2001)); P2 and N2 (Allison and Polich, 2008); late positive potential or LPP (Miller et al., 2011) have also been claimed to be diminished by increased task demands, albeit less consistently.

Taken together, ERP probes can be regarded as distractors that demand resources either through explicit competition with the primary task (Isreal et al., 1980; Wickens et al., 1984, 1983) or by implicitly drawing upon residual resources that are unconsumed by the primary task (Burns and Fairclough, 2015; Dyke et al., 2015; Miller et al., 2011; SanMiguel et al., 2008). Previous work that assessed steering demands might have required ERP probes to be task-relevant because the employed probes (i.e., beep tones) did not recruit sufficient resources to indicate the influence of steering demands.

ERP components that are elicited by distracting stimuli have been suggested to reflect three stages of distraction (Escera and Corral, 2007; Schröger and Wolff, 1998a; Wetzel and Schröger, 2014). Based on the specific ERP components that are decreased with an increase of the task demands, inferences about the stages of distraction that are influenced can be drawn. The first stage of distraction is the detection that the model of the environment was violated. When engaged in a task, participants can be expected to be primarily focused on this task. At the same time, the regularities of the acoustic environment are encoded and used to form a predictive model of the surroundings. Whenever a current event violates this predictive model, the distraction process is initiated. This first stage of distraction is reflected in the elicited ERP by the mismatch negativity (MMN). The MMN is an early, negative ERP component that is apparent in the difference wave between the distractor- and the standard stimuli, for example in an oddball paradigm. Thus, the presence of a MMN indicates early sensory detection of an unexpected change in the environment. The second stage is the, voluntary or involuntary, orientation of attention towards the distracting event. Depending on the level of readily available resources and the eliciting event, resources might be directed towards the distracting event in order to process it. This stage is reflected by the occurrence of the novelty-P3 component. The third stage describes a disengagement of resources from the distracting event and a re-orientation back to the task at hand. Disengagement from the distractor stimuli is reflected by the re-orientation negativity (RON), a late negative component. The current study investigates the influence of steering demands on ERP components that are generated by task-irrelevant auditory distractor stimuli. In the viewing baseline condition, we expect distractor stimuli to elicit ERP components that correspond to the three-stage distraction model, regardless of whether they are infrequently presented beep tones or infrequently presented environment sounds. However, we expect these ERP components to be larger when generated by environment sounds. Furthermore, we expect these ERP components to decrease when participants are required to perform a steering task, but only when they are generated by environmental distractors. We employ a data-driven approach (i.e., mass univariate analyses; (Groppe et al., 2011)) to ensure the validity of any correspondence between distractor ERP components and steering demands. This approach allows us to define each affected component in terms of its spatial and temporal characteristics, as opposed to restricting our analyses to an a priori selection of components (cf., Dyke et al. (2015); Miller et al. (2011)). ERP components that are found to be sensitive to steering demands are subsequently submitted for permutation tests to evaluate their suitability for discriminating between manipulated levels of steering difficulty. We manipulate steering difficulty by either increasing the frequency bandwidth of the disturbance that is experienced during steering (cf., Isreal et al. (1980)), or by varying the complexity of the control dynamics (cf.,Wickens et al. (1983)). We expect more participants to demonstrate a significant reduction in these targeted ERP components in the hard condition compared to the easy condition.

2.3 METHODS

2.3.1 *Participants*

We tested 24 right-handed volunteers (7 women, mean age=27.9 years, s.d.=5.2). All participants reported normal or corrected-to-normal vision, no hearing impairment and no history of neurological diseases. The experimental procedure was approved by the MPG Ethics Council and all participants gave written informed consent.

2.3.2 *Stimuli and apparatus*

The experiment was set up in a dimly-lit, low noise environment. It consisted of a primary steering task and the presentation of task-irrelevant, auditory stimuli. The steering task was presented via a central display (1027 x 581 mm, resolution 1920 x 1080 px), approximately 180 cm away from the seated participants. Auditory stimuli were presented to both ears via headphones (MDR-CD380, Sony), that where driven by a soundcard (sampling frequency: 96 kHz; DELTA1010LT, M-Audio). A secondary heads-down display informed the participants of their most recent steering performance and the current experimental status. Data collection was performed, using customized software, written in Matlab Simulink. The software version of the NASA-TLX questionnaire (Hart and Staveland, 1988) was presented on a separate notebook.

Two lines (length: 16 visual angle, thickness: 2 px) were presented on a blue background. These lines were a white horizontal non-moving reference line and a second black line that rotated around the joint center of both lines. A right-handed sidestick (Extreme 3D Pro, Logitech) with a spring constant of 0.6 N/deg was used as input device.

During the entire experiment, participants were probed with task-irrelevant stimuli with a random inter-stimulus interval (mean=1.20 s, s.d.=62 ms). Infrequently presented environmental sound distractors (prob. of presentation: p=0.1) were intermixed with frequent, standard (p=0.8) and infrequent distractor (p=0.1) beep-tones. Two easily discriminable beep-tones were used (i.e., 300 and 700 Hz) and their probability (p=0.1 and p=0.8) was counter-balanced across participants. The environmental sounds consisted of a set of 30 recognizable complex sounds (e.g. human laughter) that were selected from a database obtained from the New York State Psychiatric Institute (Fabiani et al., 1996). The environmental sounds were presented in quasi-random order without replacement. Environmental sounds, as well as standard and distractor beep-tones, had a mean duration of 336 ms (s.d.=62.5 ms) and a mean intensity of 60 dB SPL (s.d.=0.31 dB). Both, environmental and beep sounds were always preceded by at least one standard beep.

2.3.3 *Task*

Participants performed a steering task in which they were required to continuously counteract a quasi-random roll motion of a rotating line. This unpredictable roll motion was defined by the forcing function ft(t) (see Eq. (1) and Table 2). Participants were instructed to minimize the displacement e(t) of the rotating line (black in Fig. 6) relative to the reference line (white in Fig. 6), with lateral deflections of the sidestick. Task-irrelevant

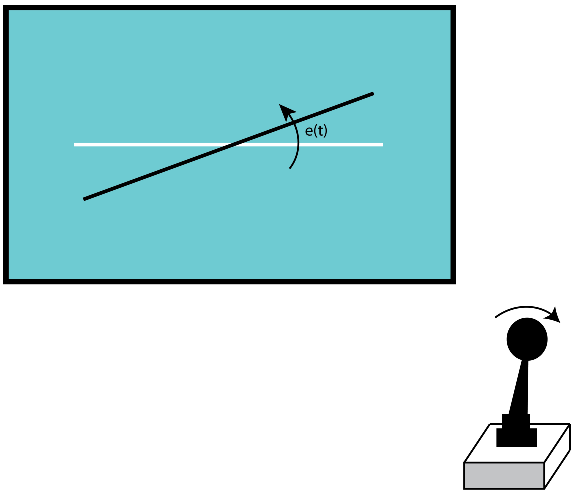

Figure 6: The steering task required the participants to counteract the quasi-random displacement e(t) of the rotating line (black) to the non-moving reference line (white), with lateral sidestick deflections.

sounds were presented that our participants were instructed to disregard. The experiment consisted of steering as well as of viewing trials. The viewing trials presented the same visual feedback in all sessions and served as a baseline. In this condition, participants viewed the steering task that was prerecorded. By comparing the steering trials against these viewing trials that both presented the same visualization, we could determine how the demands of the steering task influenced the measured ERPs, independent of the visualization.

Two aspects of the steering task were used to influence the level of workload in the task: (1) the frequency bandwidth of the roll disturbance and (2) the complexity of the internal control dynamics. In every steering trial, one of these aspects was manipulated, leading to two levels of steering task difficulty, namely easy and hard for each of the two manipulations. The second aspect was kept constant and will be referred to as standard, in the following. The objective was to create two levels of workload for independent manipulations (cf. Isreal et al. (1980); Wickens et al. (1984)). Details of these manipulations of engagement are given in the following.

Manipulation of the bandwidth of roll disturbance: The roll disturbance was designed as a sum of ten sine waves that could be manipulated for the number and intensity of roll reversals by adjusting the frequency bandwidth, such that the 'easy' condition presented less power in the higher frequencies, compared to the 'hard' condition. The standard condition was designed to be an intermediate of these two conditions.

In all conditions, the forcing function was formalized as the sum of ten sine waves that were non-harmonically related, as described in Eq. 1.

$$f_t(t) = \sum_{j=1}^{10} A(j) \cdot sin(\omega(j) \cdot t + \phi(j)) \tag{1}$$

The amplitude A(j), frequency (j) and phase (j) of these ten sine waves, for the standard, the easy and the hard condition, are given in the Table 2. The forcing function in the standard condition had a variance of 1.61 deg^2, adapted from (Nieuwenhuizen et al., 2013). In the easy condition a variance of 1.47 deg^2 and in the hard condition a variance of 1.78 deg^2 was applied.

To sum up, the hard condition presented larger amplitudes in the higher frequencies that resulted in more instances of roll-reversals than the standard and easy condition.

	Standard			Easy			Hard		
j	A(j) in deg	$\omega(j)$ in rad/s	$\phi(j)$ in rad	A(j) in deg	$\omega(j)$ in rad/s	$\phi(j)$ in rad	A(j) in deg	$\omega(j)$ in rad/s	$\phi(j)$ in rad
1	1.34	0.39	2.69	1.36	0.39	3.27	1.33	0.39	2.42
2	1.03	0.83	5.74	0.93	0.83	5.95	1.10	0.83	2.20
3	0.51	1.76	5.72	0.40	1.76	3.95	0.63	1.76	2.35
4	0.26	2.85	5.92	0.19	2.85	3.93	0.34	2.85	4.59
5	0.16	3.90	1.66	0.12	3.90	2.26	0.21	3.90	4.57
6	0.09	5.45	1.53	0.07	5.45	0.59	0.13	5.45	5.67
7	0.06	7.76	1.90	0.05	7.76	1.65	0.08	7.76	0.74
8	0.04	10.50	4.74	0.04	10.50	3.80	0.05	10.50	0.71
9	0.04	13.11	4.06	0.03	13.11	0.15	0.04	13.11	0.21
10	0.03	17.33	4.53	0.03	17.33	4.83	0.03	17.33	3.39

Table 2: Amplitude A(j), frequency (j) and phase (j) of the ten sine waves, contained in the forcing function, for the standard, easy and hard condition

Manipulation of the control dynamics: By manipulating the control dynamics, the motion of the rotating line, relative to the sidestick input of the participants, was manipulated. The control dynamics can be formally described as the transfer function H(s).

In the standard condition the transfer function had the form of:

$$H_{standard}(s) = \frac{2.75}{s(s + \omega_b)}. \tag{2}$$

This represents a hybrid controller that reacts to the sidestick input with a weighted mixture of velocity and acceleration control. In other words, depending on the frequency of the sidestick input of the participant, either the velocity or the acceleration of the rotating line was influenced. To manipulate the internal control dynamics for difficulty levels, we removed either the velocity or the acceleration component, resulting in either a pure velocity controller with the following form for the easy condition,

$$H_{easy}(s) = \frac{1.5}{s} \tag{3}$$

or a pure acceleration controller with the following form for the hard condition,

$$H_{hard}(s) = \frac{5}{s^2}. \tag{4}$$

These transfer functions were adopted from (Zollner et al., 2010). Controlling the acceleration has been shown to be more demanding than controlling the velocity (e.g. (Sirevaag et al., 1989; Wickens et al., 1984)). When the velocity is controlled, the angle of the sidestick translates to the velocity of the controlled line. In this case, keeping the sidestick in the center results in no motion of the controlled line. When the acceleration is controlled instead, keeping the sidestick in the center results in no further acceleration, but the controlled line will maintain its current velocity. Thus, participants have to anticipate the future consequence of their input commands when using a pure acceleration controller.

Design and procedure

The experiment consisted of two sessions on two separate days, one that contained the manipulation of the bandwidth of the roll disturbance and one that contained the manipulation of the complexity of the control dynamics. Session order was counterbalanced across participants. Each of the two sessions consisted of four blocks that contained three trials each. The four blocks differed in terms of the implemented difficulty (easy or hard). Each block contained two steering and one viewing trial, where the order of the trials was randomized for every participant. Each of the trials lasted 4 mins 26 s and trials were separated by 20 s of rest. During EEG preparation, participants were trained on every difficulty level and for each manipulation for at least one trial. Over the whole course of the experiment, after each trial, participants were presented with their performance (normalized root-mean-square error (nRMSerror)) to keep them motivated. At the end of each block, participants were asked to rate their perceived workload in the NASA-TLX questionnaire for each level of difficulty, separately.

EEG signal processing

The EEG was recorded with 26 active g.tec Ag/AgCl electrodes (g.LADYbird, g.tec), mounted in an elastic cap (g.GAMMAcap, g.tec). The electrooculogram (EOG) was recorded from four additional electrodes: at the outer canthi of the left and right eye, and above and below the left eye. All recorded signals were re-referenced off-line to the linked mastoids. The ground electrode was placed at FPz. The signals were amplified in the range between 0 and 2.4 kHz and digitized with a sampling rate of 256 Hz (g.USBamp, g.tec).

Further processing and analysis of the ERP signal was performed with Matlab and the open source Matlab toolboxes EEGLAB (Delorme and Makeig, 2004) and ERPLAB (Lopez-Calderon and Luck, 2014). In the off-line preprocessing, the data was high pass filtered at 1 Hz and low pass filtered at 15 Hz. Second-order Butterworth filters were used for both filters. From the filtered data, epochs from -200 ms to 1000 ms, relative to the onset of the presented sounds, were extracted. Epochs that showed blink or eye movement characteristics, in any of the electrodes, were rejected. The remaining epochs were averaged for each auditory stimulus type (environmental distractor, beep distractor, standard beep tone) and baseline corrected with reference to the pre-stimulus interval. The statistical analysis of the ERPs was based on the difference wave between ERPs that were elicited by distractors (the beep and environmental distractors, separately) and standards. This difference wave has been also referred to as distraction potential (DP) (Escera and Corral, 2003).

Statistical analysis of the ERPs

We adopted a 2-stage approach for analyzing the ERPs elicited by the environmental and beep distractors. First, we employed mass univariate analyses to: (i) determine the ERP components that were elicited by the distractors, (ii) determine the ERP components that differed between the environmental and beep distractors, (iii) identify and define the spatiotemporal characteristics of ERP components that were significantly reduced during steering, relative to the viewing baseline condition. To perform the mass univariate analyses, measured brain potentials were compared between the relevant conditions at all time points (between 100 and 900 ms after the presentation of the auditory stimuli) and all measured electrodes (26 electrodes distributed over the scalp). Two-tailed t-tests were performed between the compared conditions to yield t-values for every time-point of each electrode. The false discovery rate (FDR) was controlled using the Benjamini and Yekutieli procedure (Benjamini and Yekutieli, 2001) with a FDR level of 5%. This particular FDR procedure guarantees that the true FDR will approximate the nominal FDR level of 5%, regardless of the dependency structure of the multiple tests (a tutorial review of the mass univariate analysis is provided by (Groppe et al., 2011)). This revealed

ERP time points and their corresponding electrodes that were significantly different between the conditions.

Second, the ERP components that were identified to be sensitive to steering demands were submitted to permutation tests for each individual participant, in order to determine if these components were influenced by our difficulty manipulations for either disturbance bandwidth or control dynamics. A description of these single-subject permutation tests and their interpretation is provided by (Maris and Oostenveld, 2007). In brief, four key steps are performed for each participant: First, the selected electrodes mean amplitude over the time-range of interest was computed for every trial. Second, these mean amplitudes were submitted to a one-tailed, paired-samples t-test to yield a test t-value. Third, a null-distribution of t-values was generated. All trials were pooled and randomly distributed (without replacement) to two subsets. A paired t-test was performed between these two sub-sets to generate a single t-value. This was repeated 10,000 times to generate a null distribution. Fourth, the test t-value was compared to this generated null-distribution to determine its z-value. An alpha-level of 0.05 was adopted to determine if the tested participant showed a significant difference for the difficulty manipulations. This procedure was repeated for each participant and each ERP component of interest.

2.4 RESULTS

Steering performance and perceived workload

Steering performance and the perceived workload were analyzed for our manipulations of steering demands. This was performed independently for our manipulations of disturbance bandwidth and control dynamics complexity with the use of a paired-samples t-test. This was to validate that our participants responded appropriately to our difficulty manipulations for easy and hard. An alpha-level of 0.05 was adopted for significance testing. The Cohens d is reported for the effect size. Overall, we found medium to large effects in our manipulations of difficulty for both performance and perceived workload.

Steering performance was evaluated based on the root-mean squared deviation of the rotating line from the reference line (i.e., RMSerror). The mean RMSerror was significantly higher in the hard than in the easy condition for manipulations of the disturbance bandwidth ($t(23) = -6.6, p < 0.001, d = -1.4$) and control dynamics (t(23)=-2.2, p=0.04, d=-0.4). Perceived workload was based on the participants responses in the NASA-TLX questionnaire. The resulting workload score is the weighted sum of six subscales that were perceived by the participants as contributing to the overall workload in the following proportions: Effort: 24.5%, Mental Demand: 23.1%, Temporal Demand: 17.7% Performance: 14.3%, Physical Demand: 13.4%, and Frustration: 7.0%. The hard condition was rated as being significantly more demanding than the easy condition for both manipulations (disturbance bandwidth: t(23)=-3.4, p=0.00, d=-0.7; control dynamics: $t(23) = -3.6p < 0.001, d = -0.7$). Figure 7 illustrates the distribution of the six subscales over the two manipulations and two levels of difficulty.

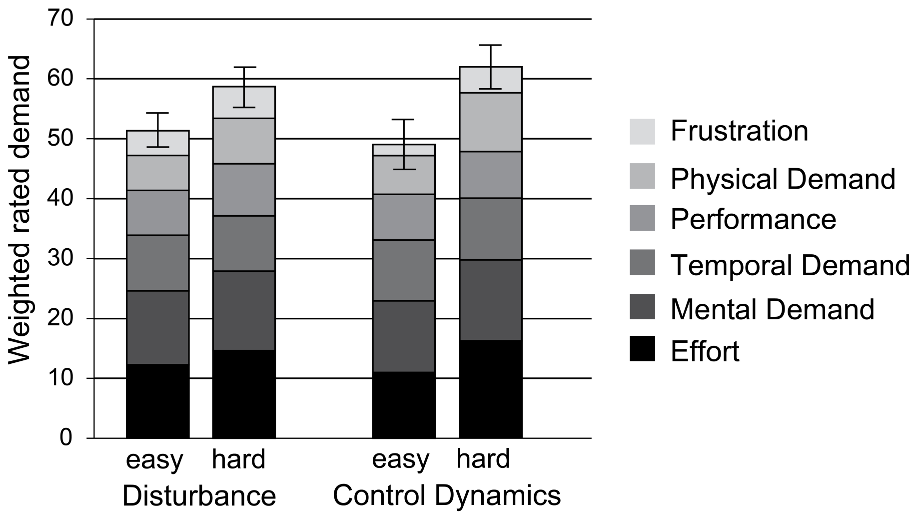

Figure 7: Weighted sum of the six subscales of the NASA-TLX that were perceived by the participants as contributing to the overall workload. The error bars represent the 95% confidence interval.

ERP results

This section is divided into three parts that describe the three analyzed aspects of the elicited ERP components. First, we present the comparison of the two distractor stimuli. Second, we present the results of the comparison between the viewing and steering trials. Third, we present the results of the comparison between the two applied manipulations of steering demands.

Comparison of the two distractor stimuli: To begin, we separately identified ERP components that were elicited by the environmental and beep distractors. Therefore, we identified, with mass univariate analysis, the time-periods for which ERP amplitudes were significantly different from the pre-stimulus time interval. Figure 8 illustrates the grand averaged waveforms and indicates significant ERP components with black bars. The environmental sounds elicited, in the steering and the viewing condition, a MMN, an early and late P3, a RON, a late positive potential (LPP) and a late negativity (LN). The beep distractors elicited a MMN, a P3a that was not further discriminable for early and late P3 sub-components, a RON, and (only in the steering condition) a LN.

Subsequently, we contrasted the ERPs that were elicited by the environmental and beep distractors. This was performed separately for the steering and the viewing trials with the use of mass univariate analyses. Figure 8 highlights (in grey) the time-periods where the ERPs of the beep and environmental distractor differ significantly. This reveals that environmental distractors generate larger P3, RON, LPP and LN components than the beep distractors. The beep distractor generated an MMN that peaked earlier than the environmental distractor.

General demands of the steering task: Here, we determined the influence of steering demands on the elicited ERP components. In the grand averaged waveform (see Figure 9), the influence of the steering demands can be mainly observed in the ERPs that were elicited by the environmental distractor stimuli and, to a lesser degree, in the beep distractors. As expected, for the ERPs that were elicited by the standard beeps the steering demands did not have a visible influence. Using a mass univariate analysis, we determined the electrodes and time points for which ERPs were significantly decreased during the steering trials, relative to the viewing trials. This was performed separately for the ERPs that were elicited by the environmental distractors and those elicited by the beep distractors. The ERPs elicited by the beep distractors were not significantly influenced by steering demands for any electrode at any time point. In contrast, the ERPs elicited by the environmental distractors were selectively decreased by steering demands at specific time-points and electrodes. Figure 10 provides a raster diagram to indicate the time-points and electrodes where ERPs of the environmental distractors were sensitive to

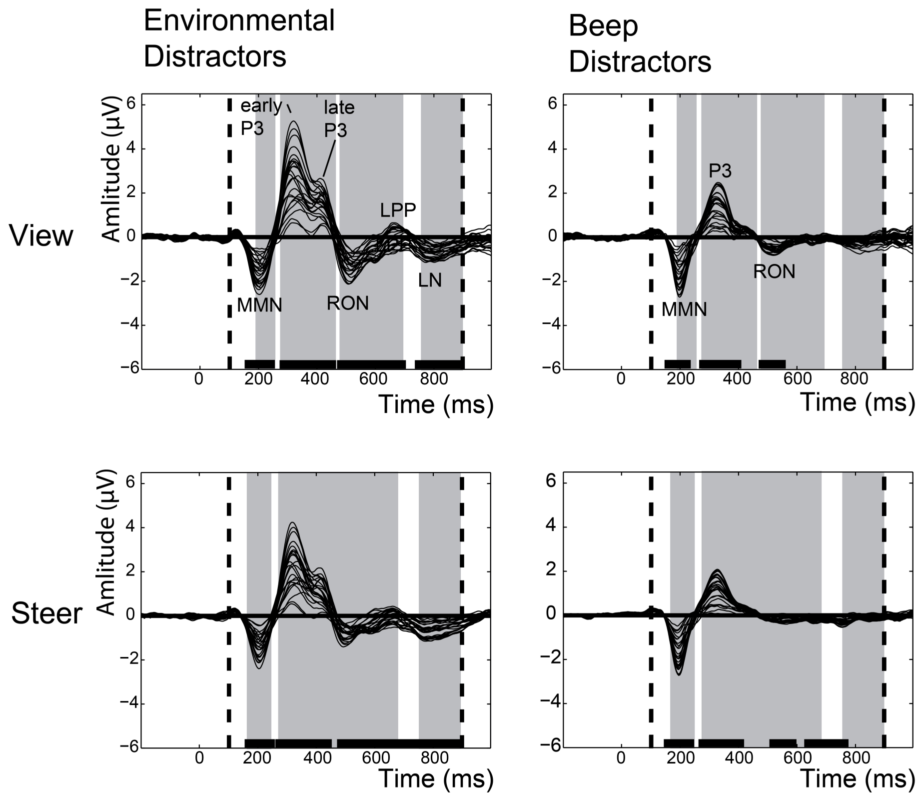

Figure 8: Grand averaged waveform of the ERPs that were elicited by the environmental distractors (left column) and the beep distractors (right column), separately for the viewing (top row) and steering (bottom row). The grand averaged waveform shows the difference wave between the ERPs elicited by the environmental/beep distractors and the standard beep-tones. Every line represents one electrode. The dashed vertical lines represent the time window of interest (100 to 900 ms). The black bars specify the time range when the ERP amplitudes were significantly different from the pre-stimulus time-interval. The grey areas highlight the time-periods where the ERPs of the beep and environmental distractor differed significantly from each other.

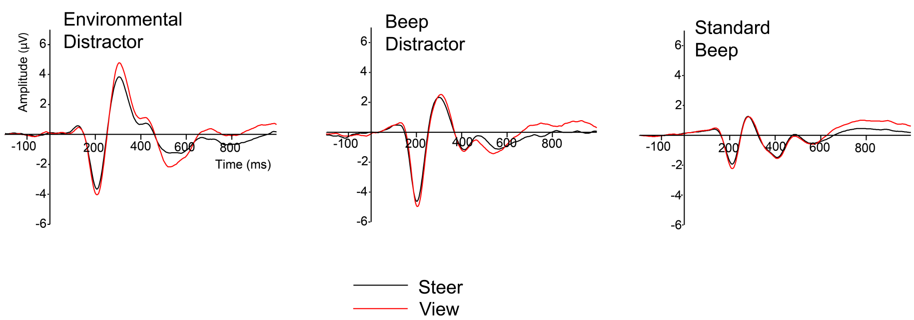

Figure 9: Grand averaged waveforms after the stimulus presentation of the environmental distractors, beep distractors and standard beeps for the viewing (red) and steering (black) trials.

steering demands. The scalp topographies for significant ERP components are provided together with the significant electrodes, indicated as white filled circles. Altogether, we find that steering demands diminish an early and late sub-component of the novelty-P3, and the RON. These ERP components have a frontocentral distribution.

Steering demands significantly decrease the early P3 generated by the environmental distractor in the time window between 280 and 330 ms in the frontocentral electrodes (AF3, AF4, F3, F4, FC5, FC1, FC2, C3, T7, Fz, Cz). The late P3 was significantly decreased between 330 and 430 ms in the central electrodes (FC1, FC2, FC6, C3, C4, CP1, CP2, P3, CP6, Cz, CPz, Pz). Interestingly, steering demands influence late P3 amplitudes at electrodes that do not correspond with the frontal electrodes, which exhibit the largest late P3 amplitudes. The RON was significantly decreased in the time window of 500 to 550 ms over the left electrodes (AF3, F3, FC1, FC2, FC5, FC6, C3, CP1, CP2, CP5, P3, PO3, Fz, Cz, CPz, Oz). Following this, we employed permutation tests to analyze the influence of steering demands on the early P3, late P3, and RON of individual participants, when elicited by environmental distractors. Single trials of the two steering conditions (easy and hard) were independently compared to the baseline viewing condition. For each participant, we submitted the recorded data from the electrodes and time points of the targeted ERP components to the permutation test. This was performed independently for the two different manipulations of steering difficulty, namely disturbance bandwidth and control dynamics complexity. Figure 11 plots the number of participants that produced significantly larger ERP amplitudes in the viewing compared to the easy or hard steering trials for the targeted ERP components.

The single-subject analysis produced results that were consistent across both manipulations (i.e., disturbance bandwidth and control dynamics complexity) and all three analyzed components (early P3, late P3 and RON). More participants showed a significant reduction in the three targeted ERP components for the hard condition than the easy condition, relative to the viewing baseline. Figure 11 also indicates differences across individuals, in terms of how they varied in response to the difficulty manipulations. White bars represent participants whose selected ERP components were diminished in both the easy and hard conditions. The dark grey bars represent participants whose ERP components were only diminished by the hard condition but not by the easy condition. The light grey bars represent participants whose ERP components were only diminished by the easy condition but not by the hard condition. Overall, the results are in line with

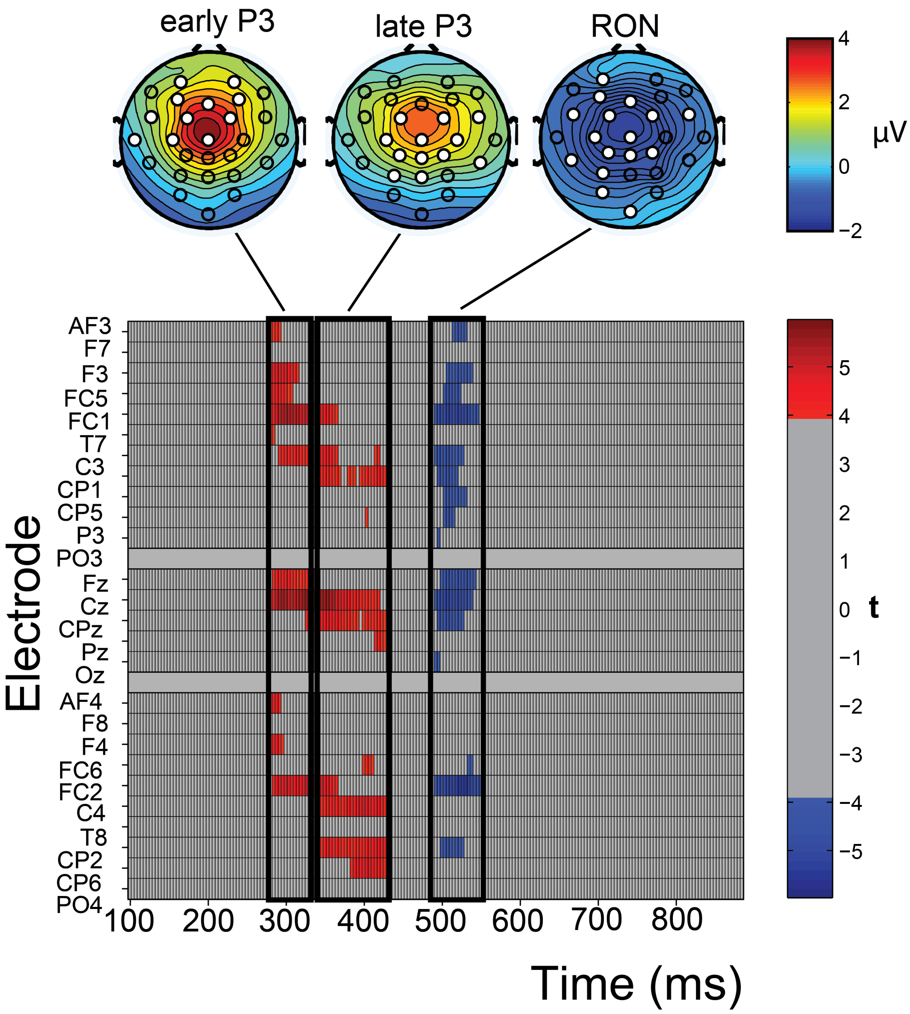

Figure 10: The raster diagram (bottom) shows the comparison results of the environmental distractor ERPs across viewing and steering trials. A mass univariate analysis analyzed every time point (256 Hz) between 100 and 900 ms for all 26 electrodes. Red/blue rectangles represent time points and electrodes where the difference between the ERPs in the viewing and steering trials was significantly positive/negative. Scalp topographies are provided (top) for the three significant time-intervals where significant differences were found. Scalp potential amplitudes are illustrated as heat maps and significant electrodes that differentiated between the viewing and steering conditions are marked white.

our expectations. More participants whose ERPs were unaffected by the easy condition were, nonetheless, affected by the hard condition than vice versa.

Influence of the steering manipulations: Permutation tests were conducted to identify the number of participants who reliably exhibited lower amplitudes for the targeted ERP components (i.e., early P3, late P3, and RON) in the hard trials relative to the easy trials. Figure 12 represents these results as gray bars. The same analysis was performed based only on the peak-amplitude electrode and corresponding time-window (i.e., 20 ms

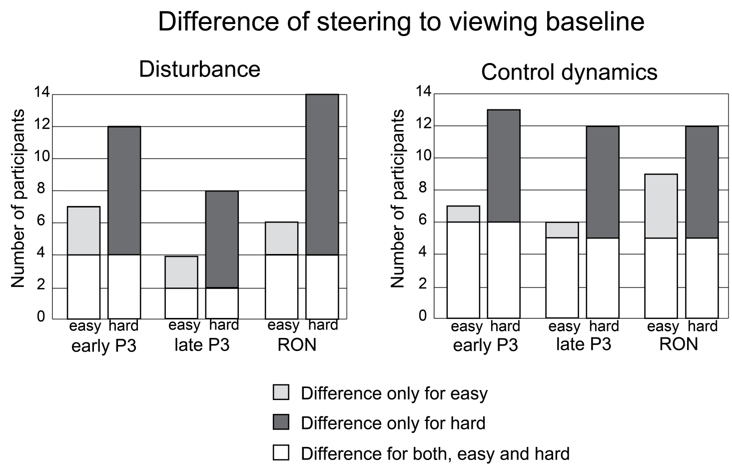

Figure 11: Permutation tests were performed to evaluate steering manipulations of the disturbance (left) and control dynamics (right). Bar plots indicate the number of participants that exhibit a significant difference in their early P3, late P3 and RON for the steering condition ('easy', 'hard') relative to the viewing baseline. White bars indicate participants who showed a reliable difference for both easy and hard conditions. Light/Dark grey bars indicate participants who showed a reliable difference for only the easy/hard condition.

around the grand average peak). This is the approach that is employed by comparable research (cf., Miller et al. (2011); Dyke et al. (2015)). Figure 12 represents these results as black bars. A comparison shows that a mass univariate analysis approach identified ERP components that were more sensitive to the current steering manipulations. Finally, more participants responded in the expected direction for the targeted ERP components when the complexity of the control dynamics was manipulated for difficulty than when the bandwidth of disturbance was manipulated.

2.5 DISCUSSION

The current study was designed to investigate if the demands of a steering task would attenuate the amplitudes of ERPs to task-irrelevant stimuli. It is in this regard that the current work sets itself apart from previous work that evaluated steering demands by measuring the ERPs to the task-relevant stimuli of a concurrent secondary task (e.g., (Sirevaag et al., 1989; Wickens et al., 1984, 1983)). The main findings of the current study are that steering demands can significantly reduce the amplitudes of three ERP components (i.e., early P3, late P3, and RON) of task-irrelevant auditory probes. However,

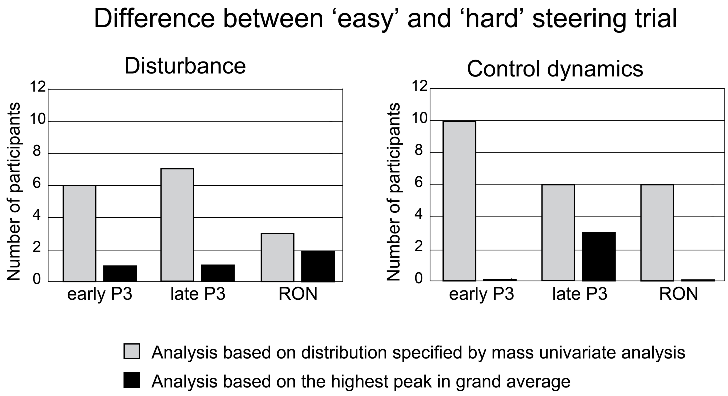

Figure 12: Permutation tests were performed to evaluate steering manipulations of the disturbance (left) and control dynamics (right). Bar plots indicate the number of participants that exhibit a significant difference in their early P3, late P3 and RON between the easy and hard conditions. Light grey bars indicate participants who showed a reliable difference between the easy and hard conditions when the analysis was based on the electrodes and time points indicated by mass univariate analysis. Black bars indicate participants who showed a reliable difference between the easy and hard conditions when the analysis was based on the peak in the grand averaged waveform.

this requires the probes to be complex environmental sounds and not simple beep-tones. Two aspects of the steering task (i.e., disturbance bandwidth and control dynamics complexity) were manipulated for steering demands and the found ERP components were significantly diminished in more participants during the difficult conditions relative to the easy conditions for both manipulations. The current results agree with a three-stage distraction model, whereby the ERP probes can be regarded as distractor stimuli that consume mental resources involuntarily (Escera and Corral, 2007; Schröger and Wolff, 1998b; Wetzel and Schröger, 2014). Therefore, we will discuss our results within this simple framework. The discussion will be organized as follows. First, we shall discuss the differences between complex environmental sounds and simple beep tones in order to understand why the former elicit ERPs that are sensitive to steering demands while the latter do not. Second, we will discuss the implications of each ERP component that was found to respond to steering demands. Third, we will discuss the observed differences in the ERPs between manipulating either the disturbance bandwidth or the control dynamics complexity.

Comparison of complex environmental sounds and beep-tone distractor stimuli

Both types of task-irrelevant distractor sounds elicited a characteristic waveform that contained ERP components, which were significantly different from the baseline (see Fig. 8). In temporal order, they are the MMN, the novelty-P3, and the RON. Respectively, they are claimed to represent the three subsequent stages of how users respond to distraction (Escera and Corral, 2007; Schröger and Wolff, 1998b; Wetzel and Schröger, 2014): (1) detection of the unexpected stimulus, (2) orientation towards the stimulus, and (3) disengagement from the distractor to re-orient back to the steering task. In other words, infrequently presented sounds are preferentially processed by the brain in spite of being task-irrelevant, whether they are complex environmental sounds or beep-tones. Two other ERP components (i.e., LPP and LN) were also elicited, but were not sensitive to steering demands.

Environmental sounds elicited ERPs that differed from the beep tones in two ways. First of all, they elicited larger ERPs. Second, their ERPs contained components that were sensitive to steering demands. These two aspects are related. To begin, it can be argued that the larger novelty-P3 and RON amplitudes (see grey areas in Fig. 8) indicate that environmental sounds recruit more corresponding mental resources than the beep sounds (Kok, 1990, 1997). This difference is apparent in the baseline viewing condition during which the participants mental resources were unoccupied and readily available. Involuntary resource recruitment is attenuated when participants are required to perform a steering task (i.e., in the steering trials), but only for the novelty-P3 and the RON of the environmental distractors (see Fig. 10). This is because the steering task reduced the amount of available resources to a lower level than task-irrelevant environmental distractors would typically recruit. In view of this, we believe that our use of task-irrelevant environmental distractors is a more direct assessment of the resource demands of the steering task, when compared to dual-task paradigms that increase the resource demands of task-relevant stimuli that actively compete for resources with the steering task (Sirevaag et al., 1989; Wickens et al., 1984, 1983).

What are the properties of environmental sounds that allow them to recruit more mental resources and, hence, generate larger ERPs even when they are task-irrelevant? Previous work suggests that distractor stimuli tend to recruit more resources if they are personally meaningful and/or exhibit high dissimilarity from their context. The personal meaning and dissimilarity from the context are respectively referred to as being stimuli specific and aspecific (Eimer et al., 1996; Hughes, 2014). Specific aspects are parameters that are inherent to the stimulus, which represent its meaning to the observer (Hughes, 2014). For example, ones personal ringtone is more distracting, as reflected by larger elicited ERPs, than another persons ringtone (Roye et al., 2007). In the current study, the environmental distractors represented familiar objects (e.g. dogs, cats, babies), which have more personal meaning than the beep-tone distractors. Thus, they can be expected to recruit more resources. Aspecific aspects of the eliciting stimulus recruit resources involuntarily due to its embedded presentation context. For example, a task-irrelevant female voice has been shown to be less distracting, as reflected by a decrease of performance in a visual recall task, when presented in a series of female voices than when presented in a series of male voices (Hughes et al., 2013). In the current experiment, we presented the environmental sounds as well as the beep sounds against a context of frequent beep tones. Arguably, environmental sounds that are a complex combination of multiple frequencies are more dissimilar to this context than their beep tone counterparts. This raised the likelihood that the environmental sounds would recruit more resources than their beep tone counterpart. To sum up, task-irrelevant stimuli are more likely to be sensitive to task demands if they are personally meaningful and differ sufficiently from their embedded context. Some studies have been reported that have been successful in using task-irrelevant beep tones to evaluate task demands. However, these studies investigated complex tasksthat is, first person shooter (Allison and Polich, 2008) and racing games (Burns and Fairclough, 2015) that, presumably, induced higher task engagement and varied in their resource demands at levels that beep tones were sensitive to. We expect the ERPs of task-irrelevant environmental sounds to be even more sensitive than beep tones to the resource demands of such complex tasks.

Influence of steering demands on the measured ERP components

The current study is the first to employ task-irrelevant ERP probes in a task that allows for the systematic manipulation of different steering demands. Such task-irrelevant probes, in particular environmental sounds, continue to elicit ERPs with components that we have identified to be selectively diminished by steering demands: early P3, late P3 and RON (see Fig. 8 and 10). As noted before, these components correspond to the mid and late stages of a three-stage distraction model (Escera and Corral, 2007; Schröger and Wolff, 1998b; Wetzel and Schröger, 2014). From the perspective of this model, steering demands did not inhibit our participants capacity for detecting unexpected occurrences. Instead, steering demands significantly diminished the extent to which available mental resources could be directed towards the processing of distractor stimuli. In turn, this hinders an efficient re-orientation away from the distractor stimuli. Altogether, these findings demonstrate that steering places demands on mental resources that would otherwise be directed towards an instinctive evaluation of unexpected events. These resources are based on attentional processes, but at a cognitive rather than a perceptual level. It is interesting to note that our participants were able to articulate this in that they rated the hard condition as being more demanding than the easy condition in terms of mental rather than physical effort (see Fig. 7). This supports our research motivation in understanding the demands of a steering task beyond its perceptual and response requirements.

The ability to maintain an appropriate level for distraction is a fundamental capability of our attentional system and a critical aspect of effective vehicle handling. On the one hand, the capacity to be distracted by unexpected events is necessary when these events reflect potential dangers in the environment. For example, the phenomenon of attentional tunneling refers to scenarios when high-performance pilots miss unexpected hazards given their increased engagement with vehicle handling. Such undesirable instances have even been observed in novel cockpit environments that are designed to promote engagement with vehicle handling, for example when synthetic vision displays with intuitive flight guidance were employed for fixed-wing control (Wickens and Alexander, 2009). On the other hand, distraction presents a danger when it interrupts and prevents one to carry out a safety-critical task. In the United States, driver distraction raises the risk of a light-vehicle near-crash/crash to approximately three times of the baseline level (Regan et al., 2011)). Task-irrelevant or task-relevant probes can be judiciously employed in steering environments depending on whether the goal is to investigate either involuntary or voluntary distraction. A perspective that considers steering environments in terms of the drivers engagement with the steering task and potential distractions (both voluntary and involuntary) is more likely to yield practical insights and operational recommendations than one that simply evaluates driving workload.

In this study, we show that both, early and late P3 components, were influenced by steering demands. These components are discriminable from each other in terms of their spatial and temporal characteristics. Functionally, the early P3 reflects a sensitivity towards violations of ones model of the environment at a post-sensory stage (Ceponiene et al., 2004). The late P3 relates to the attending of the unexpected event itself, presumably for the purpose of updating ones model of the environment when deemed necessary (Escera et al., 1998; SanMiguel et al., 2008; Yago et al., 2003). Earlier studies have provided mixed evidence on the relationship of workload and these components. Difficulty manipulations in a complex Tetris gaming environment have been found to only diminish early P3 amplitude (Dyke et al., 2015), while other studies, in particular those that target memory load, identified the late P3 as the only P3 sub-component that is influenced by workload (Escera et al., 1998; SanMiguel et al., 2008). Until the subtle interactions between workload and these P3 sub-components are better understood, we recommend employing approaches such as mass univariate analyses to determine the role of either sub-components in new task paradigms (e.g., steering), so as to reduce the risk of false positives.

Characterizing the relevant sub-components in terms of their spatial and temporal distributions provides an additional benefit. It allowed us to discriminate between manipulations of steering demands that would not be noticeable by only analyzing the peak, given inter- and intra-individual differences (cf., Dyke et al. (2015); Miller et al. (2011); Munka and Berti (2006)). In the current work, we show that more participants discriminated for the easy and hard steering trials compared to when the analysis was based on the highest peak in the grand average (see Fig. 12). Mass univariate analysis also offers an additional benefit in that it more accurately defines the spatial location of the effect of interest. In the case of late P3, we find that the electrodes that are sensitive to steering demands have a more parietal distribution than the peak amplitude electrode. This agrees with the work of Yago et al. (2003) who also defined a discriminable parietal aspect of late P3 that is claimed to be involved with working memory updating and is believed to originate from the posterior and superior parietal lobes. Besides early and late P3, we found that steering demands significantly decreased RON amplitude. RON is believed to reflect the re-orientation of attention from the distractor stimulus (Escera and Corral, 2007; Schröger and Wolff, 1998b; Wetzel and Schröger, 2014). In this sense, it can be regarded as a disengagement of resources from processing distractor stimuli. Our results are comparable to those reported by Berti and Schröger (2003) who also found that increasing workload in the primary forced-choice task reduced RON amplitudes to a distracting task-irrelevant feature. In their experiment, participants were required to discriminate between sounds with short and long durations. Infrequent changes in the task-irrelevant pitch of the sounds produced RONs with an approximate latency of 500 ms. In their experiment, workload was manipulated either by allowing participants to respond immediately or by requiring them to respond upon the presentation of the next stimuli. The latter was considered to be more difficult as it involved a stimulus-response conflict. The amplitude of RON was found to be diminished in the difficult condition. Our current results indicate that a similar RON component can be diminished by increased task demands, even when the task is presented in a separate modality from the distractor. One reason for this could be that fewer resources were available to begin with, that could be effectively engaged by the distractor stimuli. Another reason could be that mental resources are more likely to be engaged with processing distractor stimuli for longer periods of time when sub-optimal levels of resources are allocated for their processing. In this case, the disengagement from the distractor stimuli could be expected to be less efficient. Whichever the reason, it is important to realize that RON reflects resource (re-)allocation processes at a post-sensory stage and that its amplitude does not simply decrease with increased workload. In fact, RON amplitudes have been found to be larger for the 1-back working memory task than its 0-back counterpart (SanMiguel et al., 2008). In this example, the 1-back task required participants to reference information of the primary task from recent history and larger RONs could have reflected a disengagement of resources from the distractor stimulus in addition to the re-allocation of resources to task-relevant information. We believe that our manipulation of steering demands resulted in decreased RON amplitudes because it only reflected the disengagement of resources from task-irrelevant distractor stimuli. If this is true, a dual-task paradigm that entails resource competition between a steering task and a task-relevant probe should result in larger RON amplitudes when steering demands are increased.

The steering demands of manipulating disturbance and control dynamics

In the current study, we manipulated two aspects of steering that are known to influence steering demandsthat is, disturbance bandwidth and control dynamics complexity. Both manipulations of steering difficulty had an influence on the identified ERP components in the expected direction (Fig. 11 and Fig. 12). Comparatively, this influence was evident in more participants when the complexity of control dynamics was manipulated. This result is in agreement with previous work that has shown a greater sensitivity of secondary task ERPs to the manipulation of control dynamics in the primary task (Isreal et al., 1980; Sirevaag et al., 1989; Wickens et al., 1984, 1983).

While encouraging, these results should be treated with caution. Our analyses reveal that our manipulations for steering demands do not influence the identified ERP components in all of our participants. In fact, some participants responded to steering demands only in the easy but not the hard condition, albeit to a lesser extent than vice versa (Fig. 11). We believe that this reflects two aspects of inter-participant variance that are difficult to control for with the use of task-irrelevant ERP probes. First, the amount of resources that are involuntarily recruited for the processing of task-irrelevant probes. Second, steering competence and engagement with the steering task.

Participants can be expected to differ in terms of how meaningful they perceive different environmental sounds. Such differences could vary the extent to which these task-irrelevant distractors attract resources for their processing. If insufficient resources are recruited, changes in the level of available resources due to manipulations in steering demands can be expected to go undetected. To mediate this, future studies could consider employing environmental distractors that are not as easily recognizable. It has been shown that larger frontal and parietal novelty-P3s are elicited by environment sounds that are not as easily recognizable, compared to their more recognizable counterparts (Opitz et al., 1999). Moreover, it has been shown that the novelty-P3s amplitude decreases with the repetition of familiar sounds but not unfamiliar sounds, presumably because participants are more effective in ignoring them (Cycowicz and Friedman, 1998, 2007). Participants can be expected to vary in terms of steering proficiency. Therefore, some participants may only start to exhibit reduced levels of available resources under highly demanding scenarios. In fact, this is reflected in our results (see Fig. 11). The current experiment employed fixed levels of steering difficulty. Subsequent studies could calibrate levels of steering difficulty for individual participants so that their performance discriminates sufficiently between easy and hard conditions. This would be similar to the use of adaptive methods in psychophysics to calibrate stimuli settings to individual differences in perception (Kingdom and Prins, 2010).

In spite of these limitations, our current findings are consistent with previous findings. The ERP components, which we have identified as being sensitive to steering demands, are more likely to differentiate for easy and hard conditions when disturbance bandwidth was manipulated than when control dynamics complexity was manipulated (cf., Isreal et al. (1980)). This difference between the two manipulations is more prominent for early P3 and RON than it is for late P3. This suggests that increasing the complexity of the control dynamics limits how resources are directed towards and away from distractor stimuli.

Conclusion and Outlook

To conclude, we have shown that the demands of a steering task influence how the brain responds to task-irrelevant stimuli. Specifically, steering demands diminish the amplitudes of the early P3, late P3, and RON that are elicited by task-irrelevant auditory distractors, which are personally meaningful and distinct from the background. A three-stage distraction model would suggest that steering demands decreases ones sensitivity and likelihood to attend to unexpected events (early/late P3), as well as ones capacity to re-orient back to the steering task at hand (RON). In particular, we found this to be true for steering manipulations that increased the complexity of control dynamics.

The three-stage model of distraction, and its associated ERP components, is a simplification. It assumes a serial chain of information processing of the distractor stimulus and is agnostic to how the stages could be selectively influenced by factors that do not pertain to the distractor stimulus itself. Thus, its explanatory power is limited. Our finding, that environment sound distractors are more distracting than deviant beep tones (and result in larger MMN, P3a, and RON), is in line with the predictions of the three-stage distraction model. However, the three-stage distraction model does not explain why steering demands selectively influence P3a and RON amplitudes but not MMN. In fact, there is accumulating evidence to suggest that dissociations exist between the three stages of distraction. Factors such as the predictability of the distractor, which is not dependent on the distractor per se but on the homogeneity of the sequence of stimuli that precedes it, can influence MMN and P3a but not RON (Horváth et al., 2008). Converse dissociations have been reported whereby increasing the predictability of an auditory distractor with a visual cue can decrease P3a and RON amplitudes but leave MMN intact (e.g., Sussman et al. (2003)). Hence, more complex accounts have since been proposed that not only consider how distractor stimuli are processed but also how their processing might interact with the perceived regularity of the auditory scene (for example, see Bendixen, 2014). For now, it is sufficient to note that the demands of a steering task are reflected in how it modulates the distractibility of task-irrelevant environment sounds, as reflected in the early/late P3 and RON that they elicit. Besides electrophysiological responses, future experiments should be designed to investigate the behavioral consequences of distraction on steering performance (c.f., Parmentier (2014)). This could elucidate differences between distractor stimuli that passively reflect steering engagement and those that pose an involuntary conflict with the cognitive processes that underlie steering itself.

Task-irrelevant stimuli can be expected to be more easily integrated into real-world operations than the use of ERP probes that require an explicit response. In this regard, our current findings raise the opportunity of estimating steering demands across a wider range of scenarios than was previously considered to be practical. Furthermore, the use of task-irrelevant and task-relevant distractor stimuli can reveal complementary aspects of how mental resources are managed during steering. In this regard, they can be effectively employed to understand the demands of steering and users level of engagement with the steering task and their environment.

3 AUDITORY DISTRACTION IS DECREASED BY PERCEPTUAL-CENTRAL DEMANDS OF A VISUOMOTOR CONTROL TASK

This chapter has been reproduced from an article that was submitted for publication: Scheer, M., Bülthoff, H. H., Chuang, L. L. (2017). Late novelty-P3 to irrelevant environmental sounds and P3b to relevant auditory targets are selectively diminished by perceptual-central demands of continuous visuomotor control.

3.1 ABSTRACT

The brain responds to the appearance of sounds in our environment, even when they are not explicitly task-relevant. While the functional underpinnings of auditory event-related potentials (ERP) to simple pure tones are relatively established, those to complex recognizable sounds (e.g., crying baby), also referred to as environmental sounds (c.f. Cycowicz and Friedman (1997, 1998)), are less so. Such environmental sounds generate ERPs with two positive peaks (i.e., early and late novelty-P3), around the time-range where the P3 to task-relevant pure tones typically occurs. In the current work, we study the cross-modal influence of visuomotor task demands on the auditory ERPs generated by rare target tones and rare environmental sounds. Manipulating the difficulty of the visuomotor task for its demand for either "perceptual-central" or "response-related" resources had a selective influence on these ERPs. In agreement with previous work, P3 amplitudes to the target tone were selectively attenuated by the former manipulation, but not the latter. More importantly, we found that only the late, but not the early, novelty-P3 to environmental sounds was influenced in the same way. Therefore, we infer that only the late novelty-P3 resembles the P3 generated by auditory oddball targets (i.e., P3b). In light of previous research, we believe that the late novelty-P3 reflects our capacity for context updating when we encounter unexpected and meaningful events. Until now, some studies have relied on novelty-P3s to evaluate the mental workload of a main task.

The current finding allows for observed changes to novelty-P3 amplitudes to be more specifically interpreted.

3.2 INTRODUCTION

Unexpected sounds in our environment, such as a dog barking, can involuntarily attract our attention, even if we are engaged in a demanding task and the experienced sounds bear no task relevance. Task-irrelevant and infrequently presented environmental sounds, especially when embedded in the context of frequent pure tones (cf., SanMiguel et al. (2008)), generate characteristic ERPs that have been termed the distraction potential (Escera et al., 1998; Escera and Corral, 2003). In particular, the distraction potential is characterized by a prominent P3, which has been referred to as the novelty-P3 (NP3) in light of the fact that the environmental sounds that generate it are unexpected or novel and task-irrelevant. Unlike the P3s generated by pure tones (Polich, 2007), the NP3s generated by environmental sounds have two distinct and consecutive peaks, which have been termed early and late NP3 (Escera et al., 1998, 2001; Escera and Corral, 2007; Friedman et al., 2001; SanMiguel et al., 2008).
Given that environmental sounds can generate a large ERP waveform without necessitating explicit responses, they have been employed as irrelevant probes for evaluating the mental workload of participants in single-task paradigmsfor example, when solving maths problems (Ullsperger et al., 2001), or playing Tetris (Miller et al., 2011) across varying difficulty levels. Within the framework of capacity theory (e.g., Moray (1967); Kahneman (1973); Wickens (2002, 2008), the ERPs of distraction potentials reflect available resources that remain, given current task demands (Kok, 1997, 2001; Wickens et al., 1983). An irrelevant auditory probe technique offers the benefit of indexing workload without introducing the added (or interactive) demand of a secondary task for mental resources (for review, see Papanicolaou and Johnstone (1984). However, a useful interpretation of workload and task demands requires us to give name to the mental resources that a task demands in the first place. In this regard, the use of environmental sounds as an irrelevant auditory probe is severely limited by our current understanding of the

functional mechanisms that underlie the ERP components of the distraction potential. In comparison, the ERP components generated by the target tones of auditory detection tasks are better understoodin particular, the P3b generated by task-relevant targets (e.g. Parasuraman and Beatty (1980); Polich (1986); Dien et al. (2004); Verleger (1988). Broadly speaking, the P3b response to task-relevant targets is believed to reflect our capacity for recognizing an event for context-updating (Kok (2001); although, see Verleger (1988)). On the basis of this understandingand the reciprocity hypothesis (Kok, 1997, 2001; Wickens et al., 1983), which posits a simple inverse relationship between the task demands of the primary task and the remaining capacity of the brain to respond to secondary eventstarget tones have been employed in dual-task paradigms for evaluating primary task demands. Such an approach evaluates how manipulating various aspects in the primary task results in resource demands that differentially: (1) impairs secondary task performance, and (2) the ERP waveforms generated by the secondary task stimuli (i.e., target tones). For example, increasing the driving difficulty in a realistic simulator has been shown to decrease P3b amplitudes to auditory targets in a secondary detection task (Chan et al., 2016).

In the context of steering, dual-task studies have employed secondary auditory targets as ERP probes to determine the type of resources that would be demanded by manipulating various aspects of a continuous visuomotor task (i.e., manual tracking). The underlying assumption is that increased visuomotor demands for perceptual or central processing resources ought to result in diminished ERP components that correspond accordingly; for example, a smaller N1/MMN would indicate increased perceptual demands and a smaller P3b, increased perceptual-central demands (Parasuraman and Beatty, 1980; Kok, 2001). Indeed, a consistent finding has been that increasing the difficulty of a visuomotor tracking task attenuates the P3b amplitudes to secondary auditory targets, but not N1/MMN (e.g., Kramer et al. (1983); Sirevaag et al. (1989); Wickens et al. (1983)). The difficulty in visuomotor control tasks can be manipulated in various ways. Studies interested in the resource demands of visuomotor control have consistently shown that it is selectively the manipulation of the task's control dynamics that affects P3b responses to the secondary task-relevant stimuli (Kramer et al., 1983; Sirevaag et al., 1989; Wickens et al., 1983)). Other manipulations for visuomotor control difficulty do not appear to have a similar effect, in particular those that influence the properties of tracked target, such as the target's movement variance (Isreal et al., 1980), speed (Kida et al., 2004), or dimensions (Wickens et al. (1977); although, see Sirevaag et al. (1989)). Control dynamics refer to how a steering system interprets the control inputs of the participant. For example, participants could be required to control either the velocity or the acceleration of a tracked visual target. Controlling the target's acceleration, instead of velocity, could be regarded as being more effortful because it requires the participant to anticipate the future velocity of a target and, in some instances, to decelerate by moving the control device in the opposite direction of the tracked target. Thus, it is the aspects of the visuomotor task that rely on executive planning that affects the P3b components of secondary auditory targets.

In the framework of capacity theory (i.e., Wickens (2002, 2008)), this executive aspect of visuomotor control (i.e., control dynamics) is claimed to require "perceptual-central" resources, while those that influence the variability of the tracked target is claimed to require "response-related" resources. To provide a familiar example, driving a car can be said to require more "perceptual-central" resources when driving under slippery road conditions and to require more "response-related" resources when coping with extreme road curvature. The use of task-relevant ERP probes for indexing mental workload has been validated in applied settings (e.g., flight simulator: Kramer et al. (1987)) and self-reports of higher workload and performance deterioration on flight missions are typically accompanied by smaller P3bs to secondary stimuli. The terms "perceptual-central" and "response-related" resources, while admittedly vague, are founded in a framework designed for understanding task demands in operational real-world settings (i.e., Multiple Resource Theory (MRT); Wickens (2002, 2008); Wickens et al. (1983)). Here, information processing is defined by three stages (i.e., perception, cognition, and response)whereby common resources are shared by perception and cognition, distinct from those related to response generation. This distinction has also been corroborated with other psychophysiological measurements (i.e., blink rate, heart-based measures, respiration), whereby control dynamics manipulations affected components related to sympathetic cardiovascular control and target motion manipulations affected components related to parasympathetic cardiovascular control (Backs, 1997).

Environmental sounds have been employed by previous studies as irrelevant probes to index mental workload (e.g., Miller et al. (2011); Ullsperger et al. (2001)). However, this approach has been crude whereby any signs of ERP attenuation in the distraction potential to irrelevant environmental sounds is treated as evidence for increased mental workload. One reason for this is that the similarities and dissimilarities between the ERP components generated by irrelevant environmental sounds and relevant targets remain unclear. One obvious difference lies in their ERP waveforms whereby the P3b to task-relevant probes is represented by a single-peaked positive deflection between 250-500 ms, while the NP3 to task-irrelevant and unexpected environmental sounds consists of two neighboring and distinct positive deflections in the same time-range (Escera et al., 1998, 2001; Yago et al., 2003)). Thus, it is unclear whether NP3 shares any similarity to P3b, which has been used in visuomotor tasks to index "perceptual-central" resource demands, or if it should be treated as an entirely unique component.

Distraction potentials consist of three discernable components that have been argued to represent the neural correlates of three consecutive stages of distraction (Näätänen, 1990; Wetzel and Schröger, 2014). Its first component is a negative deflection (i.e., MMN/N1), which is typically generated by unexpected events that violate our expectations (Escera et al., 1998; Rinne et al., 2006). The next component is represented by two positive deflections (i.e., NP3) that reflects the orientation of attentional resources towards the unexpected event and its processing (Ceponiene et al., 2004; Dyke et al., 2015; Escera et al., 1998; Roye et al., 2007). Finally, a late negative potential (i.e,. the reorientation-negativity; RON) correlates to attentional reorientation, away from the distraction, and back to the task (Schröger and Wolff, 1998a; Schröger et al., 2000). Previous studies have shown that ERPs of the distraction potential are sensitive to primary task demands, especially the NP3 (Dyke et al., 2015; Miller et al., 2011; SanMiguel et al., 2008; Scheer et al., 2016; Ullsperger et al., 2001). The two subcomponents of NP3 and their functional similarity to P3b is the focus of our current investigation.

Unlike the P3b generated by task-relevant stimuli, the NP3 is characterized by two peaks instead of one. These have been respectively referred to as the early and late NP3 (Escera et al., 1998, 2001; Yago et al., 2003). These subcomponents are topographically distinct (Yago et al., 2003) and have been ascribed different functions (Dyke et al., 2015; Friedman et al., 2001; Gaeta et al., 2003; SanMiguel et al., 2008; Strobel et al., 2008). Gaeta and colleagues (2003) showed that the amplitude of early NP3 was comparable when it was elicited by the task-irrelevant deviant sounds, embedded in an auditory oddball task of pure tones (cf., Ullsperger et al. (2001), and when it was elicited by the task-relevant targets in the task. On the other hand, late NP3 was larger when the eliciting sound was task-relevant compared to when it was not task-relevant. Thus, it could be argued that the early NP3 component varies with the physical characteristics of the environmental sound, while the late NP3 component varies with the perceived relevance of environmental sound. This raises the question: why do environmental sounds generate a visible late NP3 component when they are task-irrelevant? Given that environmental sounds represent recognizable events, it is plausible that they are processed as relevant events even if no explicit response is required. Therefore, the early NP3 could indicate an orienting mechanism to physically interesting events while the late NP3 could reflect the extent to which environmental sounds are processed even when it bears no explicit task-relevance (SanMiguel et al., 2010).

We expect the early and late NP3 of irrelevant environmental sounds to differentiate in terms of how they are influenced by selective manipulations of a visuomotor task, for either "perceptual-central" or "response-related" resources. If the late NP3 varies according to perceived relevance, it should diminish when a visuomotor task increases its demands for "perceptual-central" resources. On the other hand, the early NP3 has been found to be more responsive to manipulations of task difficulty, albeit in a complex and poorly-understood task such as Tetris (Miller et al., 2011; Dyke et al., 2015). Previously, we have shown that simply requiring participants to perform a visuomotor control task decreases both early and late NP3 (as well as RON) to irrelevant environmental sounds (Scheer et al., 2016).

In the current study, we evaluate how manipulating the difficulty of a visuomotor task for either "perceptual-central" or "response-related" resources affect the P3bs of task-relevant secondary tone targets and the early and late NP3s of task-irrelevant environmental sounds. To do so, we employ a three-stimulus paradigm for presenting auditory stimuli (cf., Gaeta et al. (2003)). Unlike previous work that performed contrasts on hand-selected time regions of the grand average ERP (Miller et al., 2011; Dyke et al., 2015), or principal components of the ERP waveform (e.g., Kramer et al. (1983); Sirevaag et al. (1989); Wickens et al. (1983)), we employ mass-univariate analyses to identify time-electrode components that differentiate, first for the general demands of performing a visuomotor task and, subsequently, for the components that discriminate for manipulations of either "perceptual-central" or "response-related" demands. Our findings indicate that the late NP3 to task-irrelevant environmental sounds is similar to the P3b to task-relevant target tones, in terms of how it responds to manipulations of the visuomotor task. We discuss the implications of this, especially in the context of scenarios that involve visuomotor control.

3.3 METHODS

3.3.1 *Participants*

Twenty-four right-handed volunteers (7 women; mean age=24.8 years, s.d.=3.3) participated in this study. All participants reported normal or corrected-to-normal vision, no hearing impairment and no history of any neurological diseases. The experimental procedure was approved by the MPG Ethics Council and all participants gave written informed consent.

3.3.2 *Stimuli and Apparatus*

The experiment took place in a dimly-lit and quiet room and was controlled by custom-written software (Psychtoolbox 3.0 and Simulink, Matlab 2012b; The Mathworks Inc., Natick, MA, USA). The visuomotor task was presented via a large display (1027 x 581 mm, resolution 1920 x 1080 px) that was approximately 180 cm away from the seated participants. A right-handed side-stick (Extreme 3D Pro, Logitech) with a spring constant of 0.6 N/deg was used as control input device. Auditory stimuli for the oddball task were generated by a soundcard (sampling frequency: 96 kHz; DELTA1010 LT, M-Audio) and presented via headphones (MDR-CD380, Sony). Responses to auditory targets were

collected with a left-handed USB-connected button. A software version of the NASA-TLX questionnaire (Hart and Staveland, 1988) was presented on a separate notebook.
The stimuli for the visuomotor control task consisted of two lines (length: 16; thickness: 2 px), centered on a blue background (see, Fig. 13, left). They were a horizontal non-moving white line and a black line that rotated around the joint center of both lines. The quasi-random rotation of the black line was controlled by a disturbance function that was the sum of ten, non-harmonic sine waves whose amplitudes, frequencies, and phases were adapted from Nieuwenhuizen et al. (2013).
Auditory stimuli were pure tones with frequencies of 300 and 700 Hz, and environmental sounds. The environmental sounds consisted of a set of 30 recognizable complex sounds (e.g. human laughter or dog barking) that were selected from a database obtained from the New York State Psychiatric Institute (Fabiani et al., 1996). All auditory stimuli had mean durations of 336 ms (s.d.=62.5 ms) and a mean intensity of 60 dB SPL (s.d.=0.31 dB). A gradient of 10 ms was added at the beginning and end of all sounds to avoid on- and offset clicking noise.

3.3.3 *Auditory oddball detection task*

In this task, participants were presented with three possible sounds at a random inter-stimulus interval (mean=1.20 s, s.d.=62 ms): (1) frequent standard pure tones (p=0.8), (2) infrequent pure tone targets (p=0.1), and (3) infrequent environmental sounds (p=0.1). Participants pressed a USB button with their left thumb, whenever they recognized the target tone. The environmental sounds were presented in quasi-random order without replacement. Both environmental and target sounds were always preceded by at least one standard tone.

3.3.4 *Visuomotor control task*

In this task, participants were instructed to counteract the rotations of a black line by deflecting a control stick laterally, in the opposite direction. A non-moving and horizontal white line was presented as an ideal reference line. Therefore, the goal was to minimize angular differences between the white line and the black line.

Difficulty in the visuomotor control task could be manipulated in two ways (cf., Scheer et al. (2016)). First, we manipulated the control dynamics, namely how stick deflections were translated into rotation commands of the black line, by adopting the transfer functions recommended by Zollner et al. (2010). The lateral deflection of the control input could be integrated either once or twice to respectively control the velocity or the acceleration of the black line's rotation. With a velocity controller, a fixed stick deflection would ensure that the black line changes its angle at the mapped velocity in the held direction. With an acceleration controller, a fixed stick deflection would ensure that the black line steadily increased in rotational velocity with time in the held direction. Therefore, an acceleration controller requires participants to anticipate future velocities from the submitted acceleration (i.e., rate of velocity change) and, occasionally, to deflect the stick in the opposite direction of the intended direction in order to decelerate. This requirement to plan ahead instead of simply reacting to line rotations underlies the belief that acceleration control places a higher demand for "perceptual-central" resources than velocity control (Kramer et al., 1983; Sirevaag et al., 1989; Wickens et al., 1983). Second, we manipulated the frequency bandwidth of the disturbance function that controlled the rotation of the black line. Increasing the frequency bandwidth meant that the rotational disturbance changed directions more often, which made visuomotor control more unpredictable and, hence, more difficult. This places a demand on response-related resources (Isreal et al., 1980). The frequency bandwidths for low and high difficulty were designed to match the difficulty levels of operating a velocity and acceleration controller (Nieuwenhuizen et al., 2013). Only one manipulation was applied at any given time, resulting in two difficulty manipulations in the visuomotor task for either "perceptual-central" or "response-related" resources (cf. Isreal et al. (1980); Wickens et al. (1984)).

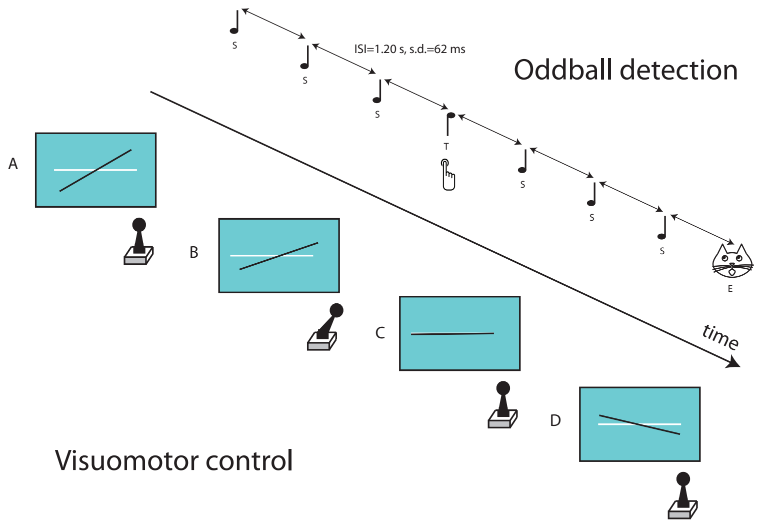

Figure 13: Left: The visuomotor control task required the participants to counteract the quasi-random displacement of the rotating line (black) to the non-moving reference line (white), with lateral sidestick deflections. A: the participants perceive the counterclockwise displacement of the rotating line B: the participants counteract this displacement by deflecting the joystick clockwise C: Due to the corrective joystick input the rotating line moves clockwise and the displacement is reduced D: The rotating line overshoots the reference line and shows a clockwise displacement. Right: The oddball detection task was presented throughout the experiment, including standard (S), target (T) and environment (E) sounds. Our participants were instructed to respond to the target pure tones as fast and accurate as possible with a button press and disregard other sounds.

3.3.5 *Procedure*

The experiment consisted of two 2-hour sessions conducted across separate days. Each session manipulated difficulty in the visuomotor task by varying either perceptual-central or response-related demands. Session order was counterbalanced across participants. Each session consisted of four blocks, evenly divided for trials with high or low visuomotor demands. Each block contained three trials, namely one baseline trial that was view-only and two trials that required participants to perform the visuomotor control task, which were randomized for presentation order. Feedback on visuomotor performance (i.e., RMSE) was presented after each trial. The auditory oddball detection task had to be performed in every trial. View-only trials presented a pre-recorded visualization of the experimenter performing the visuomotor task. The trials lasted 4 mins 26 s and were separated by a 20 s break. At the end of each block, participants rated their perceived mental workload on a NASA-TLX questionnaire.

3.3.6 *EEG signal processing*

The EEG was recorded with 26 active g.tec Ag/AgCl electrodes (g.LADYbird, g.tec), mounted in an elastic cap (g.GAMMAcap, g.tec), according to the international 10-20 system, and grounded to FPz. To detect eye-movement artifacts, the electrooculogram (EOG) was recorded from four electrodes, placed at the left and right outer canthi, and above and below the left eye. The signals were amplified in the range between 0 and 2.4 kHz and digitized with a sampling rate of 256 Hz (g.USBamp, g.tec). All recorded signals were re-referenced off-line to the linked mastoids.
Further processing and analysis of the ERP signal was performed with EEGLAB (Delorme and Makeig, 2004) and ERPLAB (Lopez-Calderon and Luck, 2014), using Matlab 2012b (The Mathworks Inc., Natick, MA, USA). In the off-line preprocessing, the data was high pass filtered at 0.5 Hz and low pass filtered at 30 Hz, using second-order Butterworth filters with 12 dB/octave rolloffs. This data was epoched for -200 ms to 1000 ms, relative to the sound presentations. Any epochs with blink or eye movement characteristics, in any of the electrodes, were rejected. To obtain the auditory ERPs for statistical analysis, remaining epochs were mean-averaged for the target tone and the environmental sound and baseline corrected to the pre-stimulus interval (i.e. -200 ms to 0 ms).

3.3.7 *Statistical analysis of the ERPs*

ERPs to the target tones and to the environmental sounds were statistically analyzed by performing two MUAs consecutively. First, an MUA was performed to determine the time-electrode components of target tones and environmental sounds that were sensitive to the added requirements of performing a visuomotor task. ERPs from the trials with concurrent visuomotor task were compared to those without a visuomotor task (i.e. view-only trials). Brain potentials were compared between the relevant conditions across 26 electrodes and 154 time points (every 3.9 ms between 100 and 700 ms after the presentation of the auditory stimuli). An MUA performs two-tailed t-tests between the compared conditions to yield t-values for every time-point of each electrode. We controlled the false discovery rate (FDR) using the Benjamini and Hochberg procedure (Benjamini and Hochberg, 1995) with a FDR level of 5% (see tutorial by Groppe et al. (2011)). Figure 16 and Figure 18 respectively illustrate the time-electrode components of target tones and environmental sounds that were significantly attenuated when participants had to perform the visuomotor task. Next, an MUA contrasted every time-electrode component that was found to discriminate for the visuomotor control task for low and high visuomotor demands. This analysis was performed separately for our difficulty manipulations of perceptual-central and the response-related demands. Therefore, we were able to evaluate if the components that were diminished by general visuomotor demands further responded to which difficulty manipulations of the visuomotor task.

3.4 RESULTS

3.4.1 *Behavioral Results*

Behavioral performance was analyzed in order to validate the task manipulations implemented in this study. First, we evaluated visuomotor task performance for our difficulty manipulations, as well as perceived NASA-TLX workload (Figure 14). Control performance (norm. RMSE) indicated that participants were affected by manipulating both ″perceptual-central″ and ″response-related″ demands. However, perceived workload was only affected by manipulations of ″perceptual-central″ demands, not ″response-related″ demands. Second, we evaluated discrimination sensitivity (d′) and correct response times (RT) in the auditory oddball task (Figure 15). Overall, the visuomotor task reduced d′ but did not slow RTs. In addition, manipulations of visuomotor demands for ″perceptual-central″, but not ″response-related″, resources decreased d′. Third, we evaluated the interference of the three sound types on the primary visuomotor task by analyzing the magnitude of control input (RMSI). The appearance of target tones

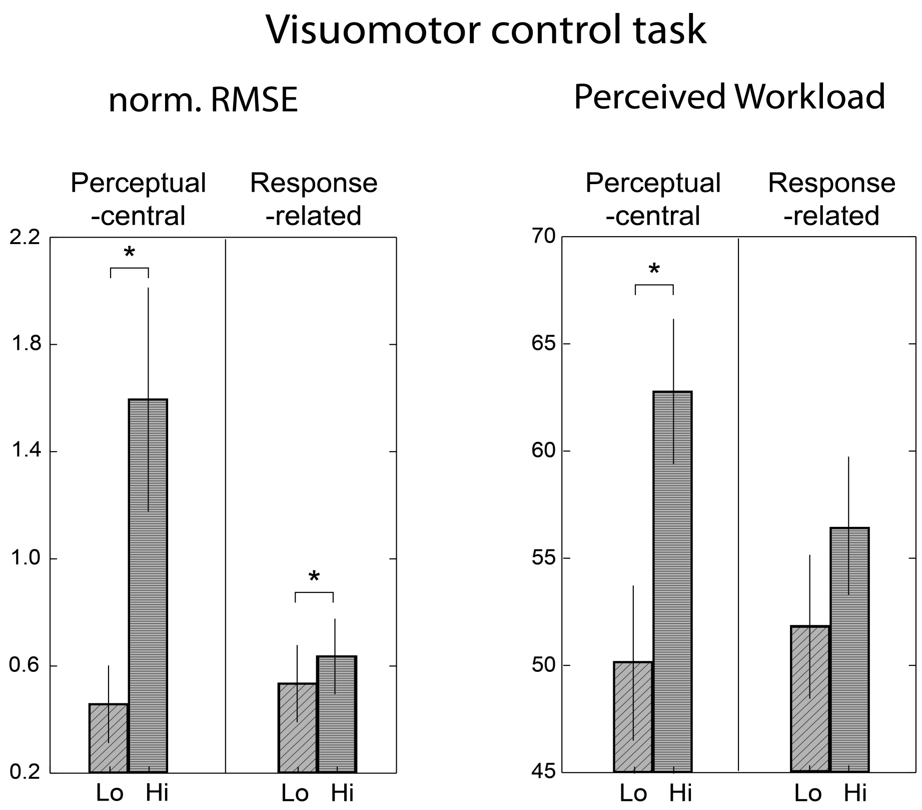

Figure 14: Primary task measures for low (Lo, grey with diagonal stripes) and high (Hi, grey with horizontal stripes) visuomotor control demands. The influence of both manipulations of demands (the demand on perceptual-central resources as well as on response-related resources) is shown. Error bars represent the 95% confidence interval, based on the Cousineau-Morey method (Morey, 2008). Significant differences between the conditions are indicated with an asterisk. On the left, the performance of our participants is depicted as normalized root mean squared error. On the right, the subjectively perceived demand, or workload, is depicted, as rated in the NASA-TLX questionnaire.

significantly reduced control input in the visuomotor task, relative to the presentation of standard and environmental sounds which did not differ from one another. In other words, there was interference at the response stage between responding to the target tone and the visuomotor task. The responses in the visuomotor task and auditory oddball were analyzed with two-tailed, paired-samples t-tests. Interference of sounds on the visuomotor task was analyzed with a 2 factorial repeated measures ANOVA for difficulty manipulation (low vs high) and sound type (target, standard, environmental). An alpha-level of 0.05 was adopted as the criteria for significance testing and details of the analyses are as follows.

In the visuomotor task, performance was measured as the normalized root-mean-squared error (norm. RMSE). This was the root-mean squared difference of the rotating black line

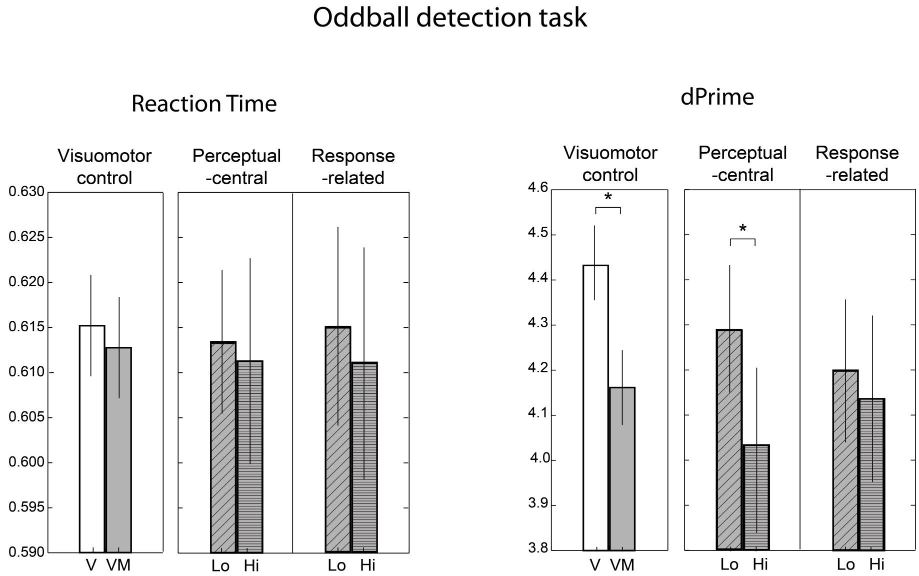

Figure 15: Oddball detection performance: reaction time (left) and dPrime (right) to the relevant pure tones. To investigate the influence of visuomotor control demands, the view-only trials (V) without visuomotor demands (white) were compared against the trials with visuomotor demands (grey, VM). In order to investigate the influence of increased demands of the visuomotor control task, the trials with low (Lo, grey and diagonal stripes) demands were compared against the trials with high (Hi, grey and horizontal stripes) demands. The influence of both manipulations of demands (the demand on perceptual-central resources as well as on response-related resources) is shown. Error bars represent the 95% confidence interval of the effect, based on the Cousineau-Morey method (Morey, 2008). Significant differences between the conditions are indicated with an asterisk.

from the white reference line across the task, divided by the root-mean squared difference of the disturbance function to the white reference line. Increasing visuomotor difficulty resulted in more control errors for our manipulations of perceptual-central demands (t(23)=4.0, p=0.001, d=0.81) and response-related demands (t(23)=3.6, p=0.001, d=0.74)). Besides this, we evaluated perceived workload in terms of self-reported NASA-TLX scores. Here, only our manipulations of "perceptual-central" demands resulted in higher scores for workload (t(23)=4.4, p=0.000, d=0.89). Increasing response-related demands did not increase the perceived mental workload (t(23)=1.8, p=0.09, d=0.37). This suggests that only the manipulation of perceptual-central demands was perceived as workload inducing.

In the auditory oddball detection task, performance was measured as detection sensitivity (d) and mean correct response times (RTs). d' scores were significantly lower when participants performed a visuomotor control task compared to view-only trials

(t(23)=3.27 , p=0.00, d=0.67). Increasing visuomotor demands for "perceptual-central" resources reduced d' in the auditory task (t(23)=2.12, p=0.045, d=0.43), but increasing demands for "response-related" resources did not have a similar influence (t(23)=0.45, p=0.67, d=0.09). RTs were not significantly different when participants had to perform an added visuomotor task (t(23)=0.43 , p=0.67, d=0.09). Similarly, manipulating visuomotor demands did not vary RTs either for perceptual-central (t(23)=0.28 , p=0.78, d=0.06) or response-related resources (t(23)=0.40, p=0.69, d=-0.08). To summarize, visuomotor task demands impaired detection sensitivity, but not reaction times, in the auditory task, particularly when perceptual-central demands were increased.
To evaluate whether the different sounds interfered with the visuomotor task, we calculated the root-mean-squared input (RMSI) of the control side-stick, relative to its upright center orientation, for the time period of 1.2 s after sound presentation. The results revealed a main effect for sound type (perceptual-central demands: $F(2,46) = 19,20, p = 0.00, \eta_p^2 = 0.46$ and response-related demands: $F(2,46) = 22.50, p = 0.00, \eta_p^2 = 0.49$). Post-hoc Bonferroni-corrected comparisons revealed that the RMSI was significantly reduced after a target tone was presented, relative to the presentation of a standard tone or environmental sound which did not differ from each other. This was true for difficulty manipulations of "perceptual-central" as well as "response-related" resources. There was also a main effect of difficulty manipulation, increasing visuomotor difficulty increased RMSI for both types of manipulations (perceptual-central:$F(1,23) = 18.08, p = 0.00, \eta_p^2 = 0.44$ and response-related: $F(1,23) = 9.28, p = 0.01, \eta_p^2 = 0.29$). Finally, there was no significant interaction between difficulty manipulation and sound type (perceptual-central demands: $F(1.37,31.57) = 3.4, p = 0.06, \eta_p^2 = 0.13$ and response-related demands $F(2,46) = 0.22, p = 0.80, \eta_p^2 = 0.01$). To summarize, target tones interfered with the visuomotor task at the behavioral level while environmental sounds did not, manipulating visuomotor demands increased side-stick activity, and the interference of target tones on the visuomotor activity was consistent regardless of visuomotor difficulty.

	ERP component	Electrodes	Time-range (ms)	General visuomotor control	Perceptual-central (electrode)	Response-related
Target	N1/MMN	AF3, AF4, Fz, F8	184:199	decrease	x	x
	P3b	FC5, FC1, T7, C3, CP1, CP5, PO3, Cz, Pz, FC6, T8, PO4	250:450	decrease	decrease (FC1)	x
	Late Positivity	AF3, F7, F3, FC5, Fc1, C3, CP1, P3, Fz, Cz, CPz, Pz Oz, AF4, F8, F4, FC6, FC2 C4, CP2, PO4	490:699	increase	x	x
Environment sound	P1	AF3, T7, C3, CP5, P3, CPz, Pz, AF4, F8, F4, Fc6, C4, CP2, PO4	109:156	increase	x	x
	Early NP3	F7, F3, FC5, FC2, T7, C3, Cz	242:270	decrease	x	x
	Late NP3	FC1, C3, CP1, CP5, P3, PO3, Cz, CPz, Pz, Oz, C4, T8, CP2, CP6, PO4	340:461	decrease	decrease (PO3, PO4, T8)	x
	RON	AF3, F7; F3, FC5, FC1, C3, P3, PO3, Fz, Cz, Pz, Oz, AF4, F8, F4, FC6, Fc2, C4, CP2, CP6, PO4	477:586	decrease	x	x

Table 3: ERP components that are influenced by visuomotor control demands. Electrodes and time-range are reported in which the ERP was significantly affected by the demand to perform the visuomotor control task. Manipulations for which no effect was present are marked with an x.

3.4.2 *ERP data*

We analyzed the ERPs that were generated by either target tones or environmental sounds. While task-relevant target tones tend to generate a single positive P3b peak, environmental sounds generate two consecutive positive peaks in a comparable time-range that we term early NP3 and late NP3. Using a mass-univariate approach (MUA), we first compared ERPs on the view-only trials against the visuomotor trials, to identify time-electrode components that were influenced by general visuomotor demands. Next, we separately analyzed these time-electrode components for their sensitivity to our difficulty manipulations in the visuomotor task for perceptual-central and response-related demands. Table 3 summarizes the ERP components that were sensitive to visuomotor manipulations. We first present the analyses on target tone ERPs, followed by those on environmental sound ERPs.

ERPs to task-relevant target sounds

General demands of the visuomotor task. Figure 16 (left) shows the grand averaged

ERP waveforms that were generated by target tones when participants performed a concurrent visuomotor task (green) and when they did not (pink). Time-intervals where ERPs differed significantly between these two conditions are marked with black bars at the bottom of the graph. The scalp topographies for each distinct time-electrode component are plotted with significant electrodes represented as white filled circles. This first analysis revealed that visuomotor demands generally decreases the N1/MMN and P3b components (see Table 3). A third time-electrode component also discriminated between visuomotor and view-only trials. Given that it overlapped with target responses, indicated by a black line at approximately 600 ms after stimulus onset, we analyzed the response-locked ERP waveform to understand this third time-electrode component better. Figure 16 (right) illustrates the response-locked ERP waveform that is epoched to button-press onset (baselined to -800 ms to -650 before button-press). The response-locked ERP is similar to the readiness potential, which is believed to reflect the preparation for a motor action, in this case a button press (Kornhuber and Deecke, 1965). The readiness potential occurs earlier in time on visuomotor trials, relative to view-only trials (see Table 3). This accounts for the third time-electrode component in the target tone ERP that is sensitive to the visuomotor task. The earlier occurrence of the readiness potential on visuomotor trials could indicate a heightened urgency, on the visuomotor trials, to respond to target tones so as to reorient one's attention to the visuomotor control task as soon as possible. This could be the basis for the lower d' scores in the auditory task, when a concurrent visuomotor task was performed.

Difficulty manipulations of the visuomotor task. The time-electrode components that discriminated visuomotor and view-only trials were subsequently analyzed with MUAs to determine which time-electrode components were sensitive to difficulty manipulations in the visuomotor task. Figure plots the grand-averaged ERP waveforms to target tones on trials with high (orange) or low demands (blue), according to whether "perceptual-central" (left plot) or "response-related" demands (right plot) were manipulated.

Only one ERP component, in the time-range of the P3b, was affected. Like previous studies (Kramer et al., 1983; Sirevaag et al., 1989; Wickens et al., 1983), increasing the demands for perceptual-central resources in the visuomotor task significantly decreased the amplitude of P3b to target tones in the concurrently performed auditory task (see

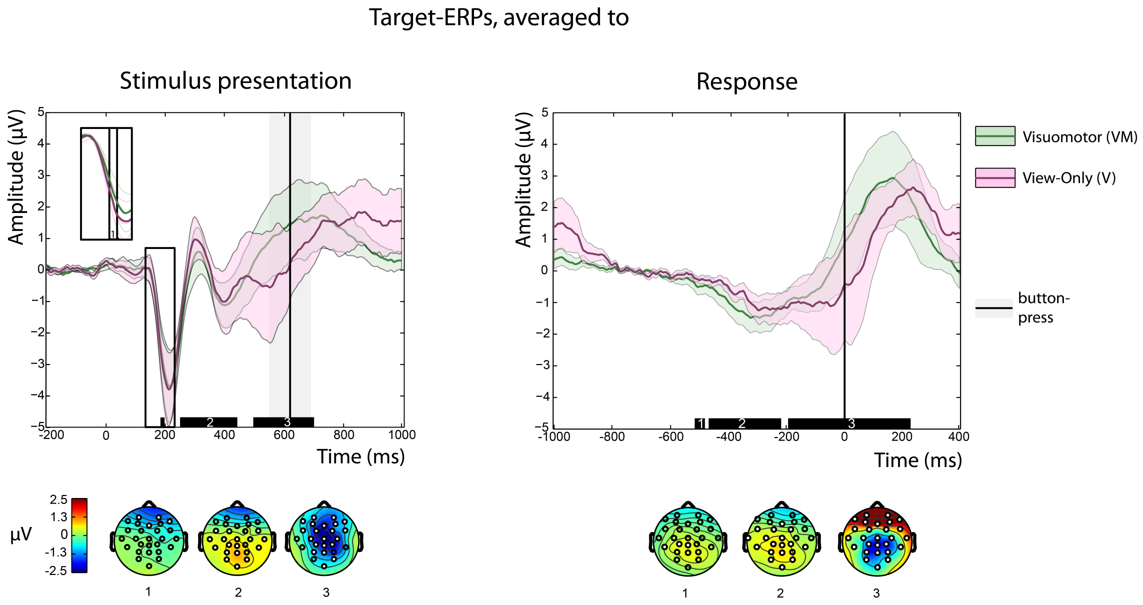

Figure 16: Target-ERPs, averaged to the presentation of the pure target tone (left) and to the button-press response of the participants (right). Top: Grand averaged ERP to the target sounds in the trials with (green) and without visuomotor control (pink). Shaded areas represented 2 standard deviations of the electrodes. The black bars at the bottom mark the time-ranges in which the target ERPs differed significantly between conditions. The black vertical line represents the mean time when our participants responded with a button press to the stimulus, with 2 standard deviations as shaded area (left). For the time range, marked with a black rectangle the significant electrodes are plotted with their mean as a zoom in the box in the upper left corner, in order to make the difference between the two conditions visible. Bottom: Scalp topographies for the found time-intervals. Scalp potentials are illustrated as heat maps and significant electrodes that differentiated between the conditions are marked white.

Table 3). In agreement with Isreal et al. (1980), increasing visuomotor demands for response-related resources did not influence any ERP components to target tones.

Task-irrelevant environment sounds

General demands of the visuomotor task. Figure 18 illustrates the grand averaged ERP waveforms generated by task-irrelevant environmental sounds on the visuomotor (green) and view-only (pink) trials. ERP waveforms to task-irrelevant environmental sounds have two positive deflections (i.e., early NP3, late NP3) in the time-range of the P3b to task-relevant target tones. Black bars indicate time-electrode components that are significantly different and their corresponding scalp topographies are provided. Requiring participants

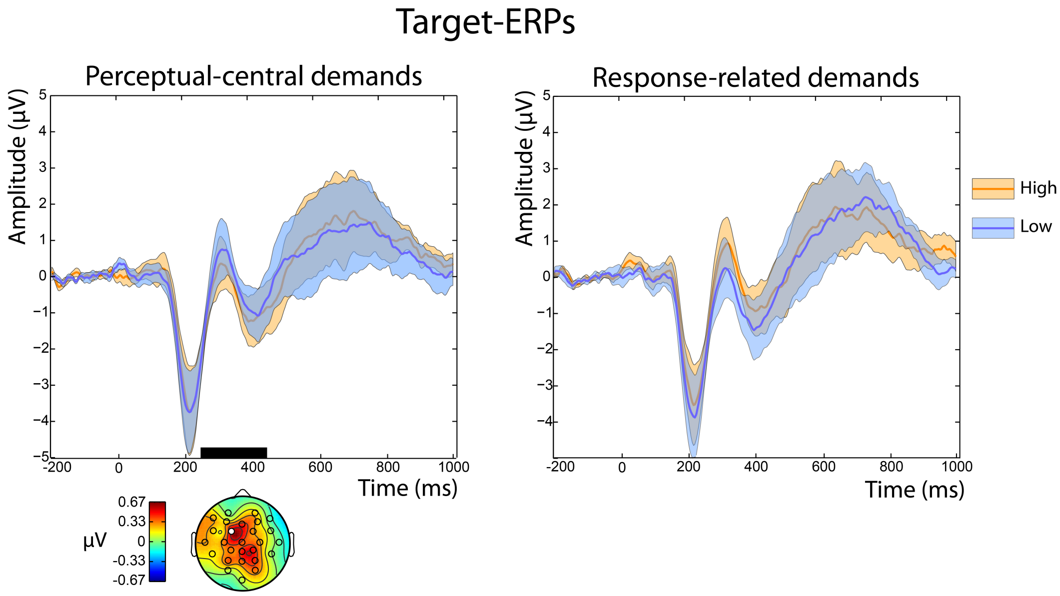

Figure 17: Top: Grand averaged ERP to the pure tone targets during trials with high (orange) and low (blue) visuomotor control demands. Shaded areas represent 2 standard deviations. The black bars at the bottom mark the time-ranges in which the ERPs differed significantly between high and low demands. Bottom: Scalp topographies for the found time-intervals. Scalp potentials are illustrated as heat maps and significant electrodes that differed between the conditions are marked white.

to perform a visuomotor task affected four time-electrode componentsit increased (1) P1, and decreased (2) early NP3, (3) late NP3, and (4) RON (see Table 3).

Difficulty manipulations of the visuomotor task. The time-electrode components that differentiated for the visuomotor task were submitted to follow-up MUAs, in order to determine the components that might respond to the difficulty manipulations in the visuomotor task. Figure 19 shows the grand averaged ERP waveforms generated by task-irrelevant environmental sounds in the trials that manipulated demands for "perceptual-central" (left) or "response-related" resources. ERPs on trials with high demands (orange) were contrasted with those with low demands (blue). An increase in perceptual-central demands only affected the late NP3 component, and not P1, early NP3, or RON (See Table 3 for details). Increasing response-related demands did not have an influence on any of the ERP components that were sensitive to the visuomotor task.

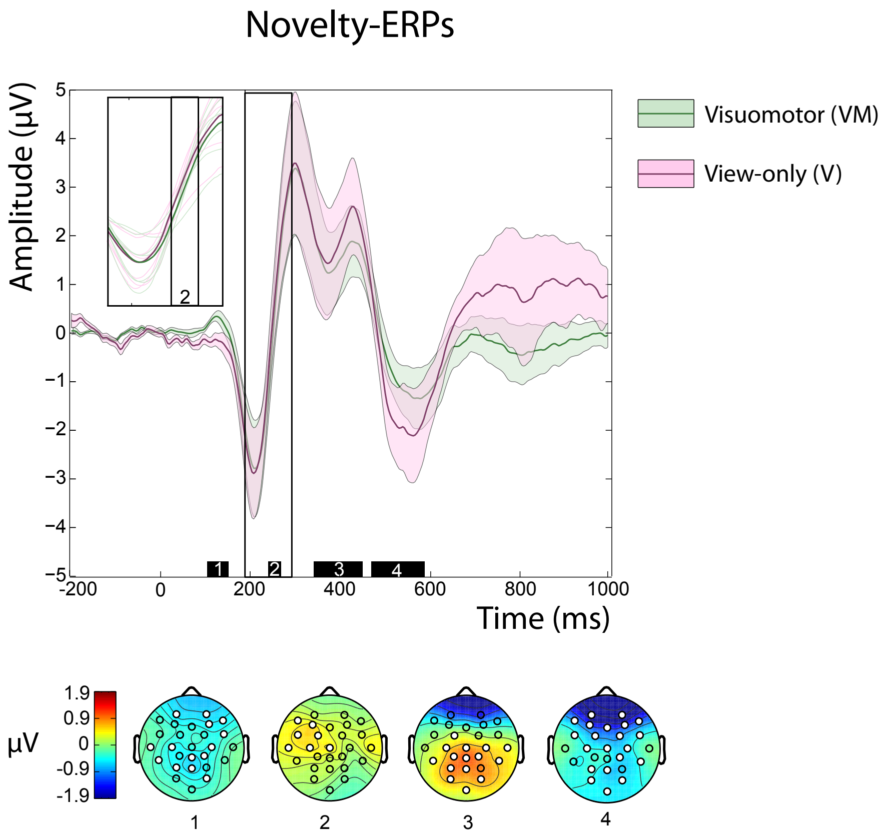

Figure 18: Top: Grand averaged ERP to the environmental sounds during trials with visuomotor control demands (green) and view-only trials without visuomotor demands (pink). Shaded areas represent 2 standard deviations of the electrodes. The black bars at the bottom mark the time-ranges in which the ERPs differed significantly between the conditions. For the second component, the mean of significant electrodes are enlarged in the inset top-left box to highlight the differences. Bottom: Scalp topographies are plotted for each significant time-interval as heat maps of the electrodes' potential and significant electrodes that differentiated between the conditions are marked in white.

3.5 DISCUSSION

The current study shows that manipulating visuomotor demands for "perceptual-central" resources attenuates the P3b of target tones in a concurrently performed auditory task as

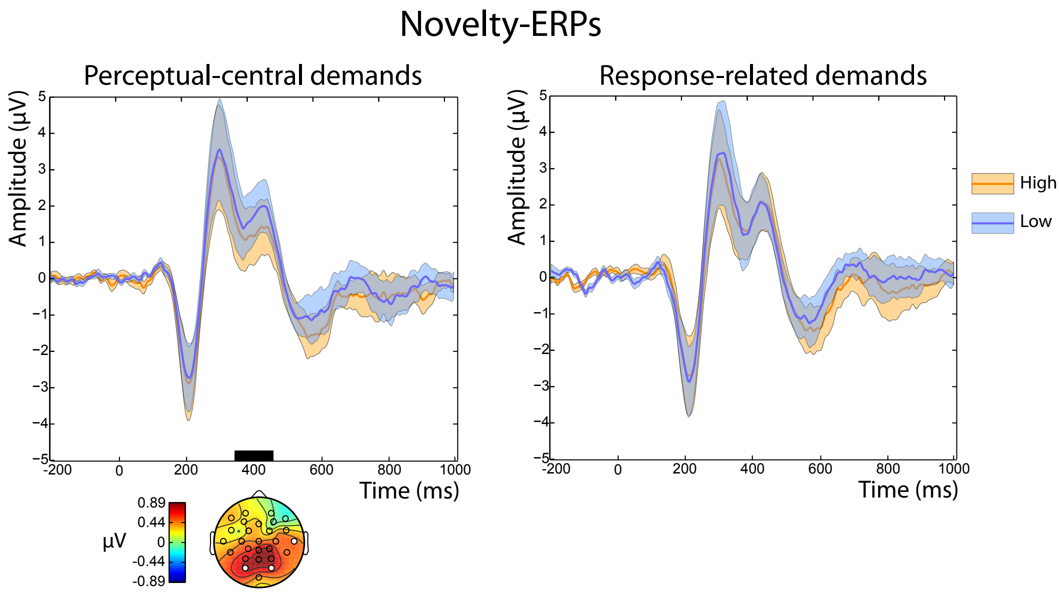

Figure 19: Top: Grand averaged ERP to the target sounds during high (orange) and low (blue) visuomotor control demands. Shaded areas represented 2 standard deviations. The black bars at the bottom mark the time-ranges in which the novelty-ERPs differed significantly between the conditions. Bottom: Scalp topographies for the found time-intervals. Scalp potentials are illustrated as heat maps and significant electrodes that differentiated between the conditions are marked white.

well as the late NP3 of environmental sounds that require no response and, hence, bear no task relevance. This leads us to infer that late NP3 has more in common with P3b, than early NP3 with P3b.

Irrelevant environmental sounds have been used as an irrelevant probe to index the mental workload of a targeted task (e.g., Miller et al. (2011); Ullsperger et al. (2001). Environmental sounds are ideal as irrelevant probes because they are more likely than pure tone stimuli, to generate ERP waveforms that are sensitive to cognitive workload. For example, previous work that similarly adopted a three-stimulus paradigm showed that the P3s of irrelevant pure tone targets are much less responsive to general task demands, compared to the NP3s of irrelevant environmental sounds (Scheer et al., 2016; Ullsperger et al., 2001). Unfortunately, only limited inferences can be drawn from the diminished ERP components of such irrelevant probes without a functional understanding of these ERP components. Therefore, the current work makes a contribution by showing that the late NP3 of irrelevant environmental sounds can be interpreted as an equivalent ERP component of P3b, at least in the context of continuous visuomotor control. Both components, late NP3 and P3b, reflect the demands of a given task on perceptual-central processing. In other words, our current finding increases the utility of the irrelevant probe technique (Papanicolaou and Johnstone, 1984), which allows targeted task demands to be evaluated without the interference of a secondary task.

By using a three-stimulus paradigm that presents both task-relevant tone targets and task-irrelevant environmental sounds, we have allowed their ERP components to be directly compared. Like that we first replicated previous findings on the influence of visuomotor demands on the P3bs of relevant tone targets. Namely, we showed that the P3bs are diminished by visuomotor manipulations in ″perceptual-central″ demands (Kramer et al., 1983; Sirevaag et al., 1989; Wickens et al., 1983), but not by ″response-related″ demands (Isreal et al., 1980). Second, we show that while late NP3s to irrelevant environmental sounds show the same pattern of responding as the P3bs, early NP3s do not. Our discussion is structured as follows. First, we discuss resource allocation between the visuomotor task and auditory processing. Next, we focus on the similarity between P3b and late NP3, and what this tells us about the functional basis of late NP3. Finally, we discuss the other components of the ″distraction potential″ (i.e., MMN/N1, early NP3, and RON) and speculate on why they were not influenced by our difficulty manipulations for visuomotor demand. To reiterate, the current work contributes to our understanding of the distraction potential and, in so doing, increase the usefulness of environmental sounds as an irrelevant probe for evaluating cognitive load.

3.5.1 *Resources shared between visuomotor control and auditory processing*

The current results verify that the resource demands of continuous visuomotor control are not entirely domain-specific. Performing a visuomotor control has a general impact on the ERP components to task-relevant auditory tone targets. It diminishes both N1/MMN and P3b components that, in the framework of capacity theory (i.e., Wickens (2002, 2008), are respectively assumed to reflect perceptual and perceptual-central processing resources (Parasuraman and Beatty, 1980). However, a visuomotor task demands different resources to cope with different aspects of task difficulty —P3b is selectively sensitive to the complexity of the control dynamics (i.e., system order of the tracking task; cf., Kramer et al. (1983); Sirevaag et al. (1989), while increasing the motion variance of the tracked target has a comparable effect on neither N1/MMN nor P3b (cf., Isreal et al. (1980). This corresponds with the insight that successful higher-order tracking requires one to attend to time-estimation as well as anticipate future events, which places a demand on executive function. In contrast, increasing motion variance in the tracked target introduces tracking difficulty in a fashion that is unpredictable, which cannot be compensated by increasing anticipatory control. In this regard, the "perceptual-central" demands of visuomotor control can be said to exert a cross-modal influence while "response-related" demands are likely to be restricted to the modality of the control task. Interestingly, the readiness potentials to auditory target responses were generated earlier when participants were required to perform an additional visuomotor task, compared to the view-only trials. Behaviorally, this manifested itself as lower discrimination sensitivity of the target tones, but not slower response times. This suggests that the continuous visuomotor control task was time-critical, resulting in more 'snap' decisions at the neural level.

How does visuomotor demands influence our ability to process irrelevant environmental sounds? With an irrelevant probe paradigm, there are no behavioral responses to indicate performance conflicts. However, we note some similarities as well as dissimilarities between the ERPs generated by the irrelevant environmental sounds (i.e., distraction potentials) and ERPs to relevant target tone. In terms of similarities, we observe amplitude attenuation, most prominently with the NP3 components. This corresponds with our previous findings (Scheer et al., 2016). The NP3 and RON components have been suggested to represent the later stages of a distraction model that respectively correspond to orienting and processing of distraction stimuli and re-orientation back to the relevant task (Escera and Corral, 2007; Schröger and Wolff, 1998b; Wetzel and Schröger, 2014). Therefore, introducing general visuomotor demands could compromise our ability to orient towards and process interesting albeit irrelevant distractor events (Cycowicz and Friedman, 1998; Gaeta et al., 2003; Strobel et al., 2008). In terms of dissimilarities, a visuomotor task does not diminish the N1/MMN response to irrelevant sounds. Rather, it diminishes the RON and augments the P1. A smaller RON could simply be the consequence of reduced NP3s, whereby the fact that fewer resources are routed to processing distractor stimuli means that fewer resources need to be re-routed back to relevant stimuli processing. It is more interesting to question why the P1 of irrelevant environmental sounds is larger when a continuous visuomotor task is introduced. The P1 has been associated with increased inhibition of stimuli processing (Hillyard and Anllo-Vento, 1998; Klimesch, 2011; Luck and Hillyard, 1995). This makes sense in the current context, if the participants perceived the environmental sounds as being task-irrelevant distractions. Presumably, increasing overall demands with the introduction of the visuomotor task further heightened the need to protect limited resources for stimulus processing. If true, the P1 of environmental sounds could also serve as an index for workload or, more specifically, greater engagement with relevant tasks.

3.5.2 *Similarity between target P3 and late novelty P3*

A more specific manipulation of the control dynamics in the visuomotor task verified the reciprocal relationship between the visuomotor task and the auditory detection task. When difficulty in the visuomotor task is increased with higher complexity of control dynamics, only the P3b to target tones is selectively diminished (cf., Kida et al. (2004); Kramer et al. (1983); Sirevaag et al. (1989); Wickens et al. (1983). The current study demonstrates that this is also true, for the late, but not the early, NP3 to irrelevant environmental sounds.

Thus, the use of existing terminology would state that late NP3, like P3b, is diminished when there is an increase in visuomotor demands for "perceptual-central" resources. Other ERP components (ie., N1/MMN, early NP3, and RON) generated by irrelevant environmental sounds are unaffected by the manipulation of control dynamics in the visuomotor task. The distinction of "perceptual-central" and "response-related" resources is relevant within the framework of capacity theories (e.g., Wickens (2002, 2008); Wickens et al. (1983). Nonetheless, the functional relevance of P3b (and by association to late NP3) is better described in terms of the perceived relevance of the target stimulus. It is well-established that P3b amplitudes are larger when the eliciting sound presents information that is perceived as being relevant for the purposes of updating one's context (Donchin, 1981; Johnson, 1984; Polich, 2007). Therefore, it is larger when an explicit response is required, when target occurrence is less frequent, and when target discrimination is difficult (Comerchero and Polich, 1999; Polich, 2007). It could be argued that environmental sounds generate a late NP3 that is functionally equivalent to P3b, even when no explicit response is necessary, because complex stimuli have a high potential of being potentially relevant for context updating. It is in this regard that the late NP3 has been claimed to resemble the P3b (Cycowicz and Friedman, 1998; Gaeta et al., 2003; Strobel et al., 2008). Findings of functional similarities between late NP3 and P3b correspond with studies that suggested a similar neural origin for the late NP3 and the P3b. At the sensor level, scalp current density analysis revealed the involvement of posterior-parietal locations in the generation of the late NP3 (Yago et al., 2003), a location that is typically linked to memory storage operations and the generation of P3b (Brázdil et al., 2001; Knight, 1996). Besides this, independent component (IC) analyses have also showed that an IC cluster in posterior brain regions that characterized the ERP to relevant target tones contributed substantially to the NP3 to environmental sounds as well (Debener et al., 2005). In their neuroanatomical model, Corbetta and Shulman (2002) proposed that a dorsal network (i.e., intraparietal and superior frontal regions) supported the top-down attention while a ventro-frontal network (i.e., temporoparietal and inferior frontal cortex) supported bottom-up attention for unexpected but potentially relevant stimuli. From this, we might expect irrelevant environmental sounds to be exclusively processed by the ventro-frontal network. Nonetheless, a simultaneous EEG/fMRI study showed that targets and environmental sounds induced activation in overlapping regions that corresponded to both networksdorsal network: the posterior intraparietal sulcus and precentral sulcus; ventro-frontal network: posterior temporal gyrus and inferior frontal gyrus (Strobel et al., 2008). Therefore, the authors' suggested that this reflected the brain's capacity for processing stimulus salience, which could be defined by a stimulus' rare occurrence, task relevance, novelty and complexity. In summary, previous studies and the current work have demonstrated that the P3b to relevant targets and the late NP3 to irrelevant environmental sounds bear functional similarities (Cycowicz and Friedman, 1998; Gaeta et al., 2003), with a high likelihood of common neural generators (Debener et al., 2005; Strobel et al., 2008; Yago et al., 2003). Functionally, both components are likely to reflect the updating of the working memory for context. While it might seem surprising that task-irrelevant sounds induce context-updating, this could indicate an involuntary mechanism that serves to continuously refine our predictive model of the environment (Schröger et al., 2015a,b).

3.5.3 *Other components of the distraction potential*

Irrelevant environmental sounds generated other ERP components (i.e., P1, early NP3, RON) that were affected by general visuomotor demands but were unaffected by any manipulations in the visuomotor task for either "perceptual-central" or "response-related" demands.

In particular, it is interesting to note that early NP3 is insensitive to the selective manipulations in visuomotor demands. This further underlines the belief that although both early and late NP3 components are generated by environmental sounds, they are functionally distinct. Similar findings have been found in a separate study that employed as its primary task, an n-back working memory task (SanMiguel et al., 2008). Like the current study, this study showed that working memory load manipulations diminished the late NP3 of irrelevant environmental sounds but not the early NP3. In this regard, manipulations of working memory load and the complexity of a visuomotor task's control dynamics place similar demands on "perceptual-central" resources that do not interact with early NP3. It is worth mentioning that the opposite trend has been noted in other studies that have similarly used environmental sounds as irrelevant probes for indexing mental workload, namely, the amplitude of early NP3, and not late NP3, varied with the difficulty of the main task (i.e., Tetris; Dyke et al. (2015); Miller et al. (2011). It is unclear why a difference exists between these studies. However, the complexity of Tetris and the demands that it places are likely to be multivariate and more complex than our current manipulations of control dynamics or working memory load. Taken together, such differences demonstrate that it is potentially misleading to treat ERP components as measures of task demands prior to understanding their functional underpinnings.

Like early NP3, the RON was unaffected by our difficulty manipulations in the visuomotor task. This is surprising, as previous studies have shown the RON to be diminished by increased working memory demands (Berti and Schröger, 2003; SanMiguel et al., 2008). One key difference between the current study and such other studies lies in our use of the visuomotor task as the primary task. The visuomotor task is a continuous task that demands constant attention. In contrast, other studies have typically employed a primary task (i.e., n-back working memory task) that presents discrete stimuli (e.g., Berti and Schröger (2003); SanMiguel et al. (2008)). Therefore, the RON in our current study did not have a fixed latency to any discrete stimuli in a primary task. Therefore, it does not reflect a reorientation back to the main task (i.e., visuomotor steering) for which difficulty was manipulated, but reflects a preparation for the next stimulus in the auditory for which difficulty was not manipulated (Escera et al., 2001).

3.5.4 *Overall conclusions*

The current work introduced the use of a continuous visuomotor task to evaluate the similarities, if any, between the ERP components generated by task-irrelevant environmental sounds and task-relevant tones. We found the late NP3 of environmental sounds to be similarly sensitive as the P3b to target tones to difficulty manipulations in the control dynamics in the visuomotor task. This manipulation in the visuomotor task has conventionally been described as one that affects the availability of "perceptual-central" resources. This is plausible given parallels between our current manipulation and other studies that manipulate working memory load instead. Overall, we believe that late NP3, like P3b, reflects the mechanisms that underlie our ability for context-updating, regardless of whether the presented stimulus is one that explicitly demands a response or otherwise. If true, environmental sounds are viable irrelevant probes for the purposes of evaluating one's spare capacity for context-updating, given current task demands.

4

AUDITORY DISTRACTION IS DECREASED WHEN THE AUDITORY MODALITY IS TASK-IRRELEVANT

This chapter has been reproduced from an article that was submitted for publication: Scheer, M., Bülthoff, H. H., Chuang, L. L. (2017). Auditory irrelevance: Auditory task irrelevance: A basis for inattentional deafness.

4.1 ABSTRACT

Objective: This study investigates the neural basis of inattentional deafness, which could result from task irrelevance in the auditory modality. **Background:** Humans can fail to respond to auditory alarms under high workload situations. This failure, termed inattentional deafness, is often attributed to high workload in the visual modality, which reduces one's general (and cross-modal) capacity for information processing. Besides this, our capacity for processing auditory information could also be selectively diminished if there is no obvious task relevance in the auditory channel. This could be another contributing factor, given the rarity of auditory warnings.

Method: Forty-eight participants performed a visuomotor tracking task, while auditory stimuli were presented: a frequent pure tone, an infrequent pure tone, and infrequent environment sounds. Participants were required either to respond to the presentation of the infrequent pure tone or not. We recorded and compare the event-related potentials (ERPs) that were generated to the environment sounds, which were always task-irrelevant for both groups. This served as an index for our participants' awareness of the task irrelevant auditory scene.

Results: Manipulation of auditory task relevance influenced the brain's response to task irrelevant environment sounds. Specifically, the late novelty-P3 to irrelevant environment sounds, which underlies working memory updating, was found to be selectively enhanced by auditory task relevance.

Conclusion: Task irrelevance in the auditory modality selectively reduces our brain's

responses to unexpected and irrelevant sounds, regardless of visuomotor workload. **Application:** Presenting relevant auditory information more often could mitigate the risk of inattentional deafness.

4.2 INTRODUCTION

Inattentional deafness (ID) refers to the neglect of unexpected auditory information. This is a safety critical issue, particularly in scenarios that rely on auditory warnings (e.g., Bliss (2003)). For example, Dehais et al. (2014) reported that 11 out of 28 highly-trained pilots failed to notice the auditory alarm for landing gear failure that occurred simultaneously with a buffet-inducing windshear. Typically, ID is attributed to the reduced availability of cross-modal attentional resources to process auditory information, caused by high perceptual load in the competing visual modality (Macdonald and Lavie, 2011; Molloy et al., 2015; Raveh and Lavie, 2015). Thus, the demands of visuomotor control caused by sudden windshear in the example provided above (i.e., Dehais et al. (2014)) consumed the available mental resources that would, otherwise, have gone towards recognizing and responding to the auditory alarm. This account is supported by both psychophysical as well as neuroimaging evidence. To test for ID, participants are often required to perform visual tasks of varying perceptual difficulty while irrelevant sounds are presented in the background (Macdonald and Lavie, 2011; Raveh and Lavie, 2015). Those who experience high visual load (e.g., discriminate two lines for their lengths; 3.6 vs 3.8) are less likely to hear unexpected sounds when probed after its occurrence than those who performed an easier task (e.g., discriminate two lines for their colors; blue vs green). Besides behavioral results, Molloy et al. (2015) reported that increasing visual search difficulty attenuated auditory evoked potentials of Magnetoencephalographic (MEG) recordings, to irrelevant audio tones. In other words, information processing demands in the visual modality reduced brain responses and thus the ability to detect irrelevant stimuli in the auditory modality. This finding agrees with neuroimaging studies conducted in experiments resembling flight control scenarios (Dehais et al., 2016; Giraudet et al., 2015; Scannella et al., 2013). In an EEG/ERP study, participants were presented with video clips of a

Primary Flight Display with flight indicators and were required to decide if landing was feasible or not, while responding to auditory targets when they occurred. Here, participants were more likely to miss alarms when the simulated scenario presented indicator values that suggested degradation of aircraft status (i.e., heading, magnetic declination, wind speed). More importantly, ERP responses to the presentation of target tones in such high-load aviation-decision scenarios exhibited a smaller P300 component—namely, a positive deflection in the Pz electrode recording, around 450-600 ms post sound presentation—than low-load scenarios (Giraudet et al., 2015).

The amplitude of ERP components to visual or auditory stimuli can be treated as an index for information processing—namely, how aware one is of the presented stimuli. Function can also be ascribed to the different components, indicated by time-varying peak deflections in the ERP. An influential account of the functional distinction has previously been provided by Parasuraman and Beatty (1980) whereby the early negative deflection (i.e., N100) is likely to reflect event detection while the later positive deflection (i.e., P300) is associated with both event detection and recognition. With this in mind, the reported finding of Giraudet et al. (2015) suggests that high load scenarios that are encountered in the visual domain reduces the brain's capacity to recognize task-relevant events in the auditory domain.

Dual-task paradigms are often employed to study resource conflicts across operational domains (e.g., driving while using the phone). With EEG/ERP measurements, it is possible to investigate, not only the behavioral consequences of resource conflicts but also, in terms of potential conflicts of information processing at the neural level (e.g. Wickens et al. (1984). In the context of steering, increasing the difficulty of a primary visuomotor control task results in larger ERP amplitudes (i.e., P300) to secondary task stimuli if they are presented visually, while smaller P300 amplitudes are associated with secondary task stimuli that are presented in the auditory modality (Sirevaag et al., 1989; Wickens et al., 1983). This concurs with a basic tenet of attentional load theory (Lavie, 2005, 1995) whereby perceptual load in one modality biases the allocation of cross-modal resources to one modality at the cost of another. Until now we have addressed the evidence for a popular account of ID, namely that it is a consequence of cross-modal resource competition at the neural level. Nonetheless, there exists another viable cause for ID, which is not mutually exclusive with attentional load theory. Until now, ID is said to occur because of a lack of available resources for processing auditory information. However, cross-modal competition is not a necessary condition for this to happen. A lack of obvious task demands in the auditory domain could also diminish the brain's capacity to respond, process, and identify auditory information. In other words, while ID could result from an active fatigue of cross-modal resources, which is the favored account thus far, it could also result from the passive fatigue of resources selective for auditory processing (see Desmond and Hancock (2001); May and Baldwin (2009)). In the context of driving, long durations of experiencing a monotonous environment (e.g., a straight road) has been shown to result in worse steering (Thiffault and Bergeron, 2003), which is referred to as a consequence of underload as opposed to overload. According to one account, underload conditions cause operators to withdraw resources from a task and induce them to rely on mental schemas of the task scenario instead (Gimeno et al., 2006). Given that auditory alarms tend to occur infrequently, the constant vigilance for rare auditory warnings, even if it is expected of a skilled operator (cf., Dehais et al. (2014), is resource inefficient (Desmond and Hancock, 2001; Gimeno et al., 2006; Manly et al., 1999).

With this in mind, we would like to revisit the first example that was provided for ID (i.e., ID for aviation warnings during flight control; Dehais et al. (2014)). In this study, the authors observed that participants who had experienced and noticed a critical auditory alarm in the first trial were five times more likely to detect it in subsequent trials, even in windshear conditions that imposed high visuomotor demands. Given this, we currently posit that ID results from a combination of active fatigue—due to the crossmodal demands from the visual domain, e.g., vehicle handling (Dehais et al., 2014), visual search (Raveh and Lavie, 2015), aviation-landing decision (Giraudet et al., 2015)—as well as passive fatigue in the auditory modality due to the absence of obvious task demands.

How can we evaluate the possibility that the absence of obvious task demands in the auditory domain reduces our capacity for processing sounds? In the current work, we do so by measuring the involuntary neural responses of our participants' brains to task-irrelevant sounds in its auditory environment. Complex environmental sounds (e.g., human laughter, dog barks) are known to generate characteristic ERPs (termed distraction potentials; (Escera and Corral, 2003) even when they bear no task relevance. Moreover, deflections in these distraction potentials are respectively associated with our capacity to be detect (N1), recognize (early novelty-P3; e-nP3), and update our working memory for changes in our (auditory) environment (late novelty-P3; l-nP3). In previous work, we established that visuomotor control demands can diminish the late neural responses (i.e., e-nP3 and l-nP3) to task-irrelevant environmental sounds (Scheer et al., 2016). Others have shown similar findings with visual tasks such as playing Tetris (Dyke et al., 2015; Miller et al., 2011). This reflects cross-modal demands of the visual modality on auditory processing.

In the current work, we required half of our participants to perform an auditory detection task for target pure tones while performing a visuomotor control task (i.e., compensatory roll compensation with rotor-craft dynamics). Given the theorizing thus far, we hypothesize that selective ERP components to task-irrelevant environment sounds will be larger when the auditory modality is task relevant compared to when participants are not required to monitor it. Furthermore, we believe that such an effect would reflect the allocation of modality-specific resources to the auditory modality and should, hence, be independent of cross-modal demands imposed by a visuomotor task. Finally, the affected ERP component(s) will allow us to infer the stage of auditory information processing that suffers during ID from a reduced capacity by our manipulation of auditory irrelevance, which is independent of those imposed by general cross-modal task demands. The implications of this are discussed in more detail after the results are presented.

4.3 METHODS

4.3.1 *Participants*

48 right-handed volunteers (14 females) with a mean age of 26.33 years (standard deviation (s.d.) = 4.58) participated in this study. All participants provided signed

informed consent and reported normal vision and hearing, and no history of neurological diseases. The experimental procedure was approved by the MPG Ethics Council.

4.3.2 *Stimuli and Apparatus*

The experiment was conducted in an isolated cubicle with a central large display (1027 x 581 mm, 180 cm away) for the visuomotor task and a secondary display that provided tracking performance feedback after each trial. Auditory stimuli were presented via stereo headphones (MDR-CD380, Sony) and a soundcard (sampling frequency: 96 kHz; DELTA1010LT, M-Audio). Customized software in Matlab Simulink controlled the experiment and data collection, and NASA-TLX responses (Hart and Staveland, 1988) were collected with a laptop.

In the visuomotor task, a white static reference line and another black line that could rotate around the joint center of both lines (length: 16 visual angle, thickness: 2 px) were presented against a blue background, to simulate an attitude indicator. A right-handed sidestick (Extreme 3D Pro, Logitech) with a spring constant of 0.6 N/deg was used as input device for the visuomotor task. Black line rotations were controlled by a multi-sinusoidal function, comprising 10 non-harmonic frequencies that simulate roll disturbances (Scheer et al., 2016).

The auditory stimuli consisted of three sounds, two easily discriminable pure tones (i.e., 300 and 700 Hz) and environment sounds. One of the pure tones was presented 80% of the time and the other, 10% of the time. Environment sounds occurred 10% of the time and were randomly sampled from 30 recognizable complex sounds (e.g., human laughter) that were selected from a database with standardized naming norms (Fabiani et al., 1996) and were repeated 13 times each. All auditory stimuli had a random inter-stimulus interval (mean=1200 ms, s.d.=62 ms), a mean duration of 336 ms (s.d.=62.5 ms) and a mean intensity of 60 dB SPL (s.d.=0.31 dB). To prevent on- and offset clicks, all auditory stimuli began and ended with a 10 ms linear intensity gradient.

4.3.3 *Experimental task*

All participants performed a visuomotor control task, which was to stabilize a horizontal line by manipulating a right-handed side-stick laterally in order to counteract quasi-random roll disturbances about the line's center. Half of the participants (7 females, mean age=27.9 years, s.d.=5.20) were instructed to monitor the auditory channel and to respond with a left-handed keypress when they heard a deviant pure tone, namely the one that occurred less frequently. The remaining participants (7 females, mean age=24.75 years, s.d.=3.27) were instructed to disregard all auditory information. Participants of both groups were told to ignore the environment sounds. A third of the trials did not require participants to perform the tracking task. Pre-recorded visual feedback from the experimenter performing the tracking task was presented instead. Participants performed the auditory detection task if it was required.

4.3.4 *Design and procedure*

The experiment is a between-group design for the main factor of auditory relevance. The experiment consisted of eight experimental blocks that were distributed over two days. Each block comprised two visuomotor ("Visuomotor") trials and one viewing trial ("View"), presented in random order. Each trial lasted 4 mins 26 s, with a 20 s break in between. Participants practiced the visuomotor task during EEG preparation, which lasted 15 mins. Auditory stimuli were only presented on the test trials. After every trial, feedback was provided for visuomotor performance (i.e., normalized root-mean-square error). After every block, participants were asked to self-report perceived workload on a NASA-TLX questionnaire.

4.3.5 *EEG recording, signal processing and statistical analysis*

EEG recording were obtained from 26 recording sites based on the International 10/20 system and a ground lead (Fpz), using active g.tec Ag/AgCl electrodes (g.LADYbird, g.tec) that were affixed to participants' heads with a standardized elastic cap. To identify eye-movement artifacts (e.g., blinks), electrooculogram (EOG) recordings were obtained from four additional electrodes, placed at the outer canthi of both eyes, and above and below the left eye. Each electrode signal was re-referenced off-line to linked mastoid recordings prior to analysis. The signals were amplified in the range between 0 and 2.4 kHz and digitized at a sampling rate of 256 Hz (g.USBamp, g.tec). Signal processing and analysis of the ERP signal was performed using Matlab (MathWorks Inc., USA) and open-source toolboxes EEGLAB (Delorme and Makeig, 2004) and ERPLAB (Lopez-Calderon and Luck, 2014). EEG recordings were high-pass filtered at 0.5 Hz and low-pass filtered at 30 Hz using second-order Butterworth filters, with rolloffs of 12 dB/octave. From the filtered data, epochs from -200 ms to 1000 ms, relative to the presentation onset of environment sounds, were extracted. Epochs were rejected if they contained blink or eye movement contamination in any electrodes. Remaining epochs were averaged and baseline corrected with reference to the pre-stimulus interval (-200 to 0 ms).

The ERPs generated by environment sounds were submitted to a mass univariate analysis (MUA) for the between-group factor of auditory relevance. This allows us to identify the time-electrode components that were significantly influenced by the manipulation of auditory relevance. Briefly, multiple two-tailed t-tests were applied to the ERPs across the test conditions for auditory relevance to yield t-values for every electrode and every 3.9 ms time-bin (between 100-700 ms post environment sound onset). The false discovery rate (FDR) was controlled to ensure a true FDR of 5% in spite of multiple testing (Benjamini and Hochberg (1995); for details and a tutorial, see Groppe et al. (2011). To investigate whether auditory relevance and visuomotor demands interacted, a difference waveform was derived from auditory relevance and irrelevance ERPs and the MUA was repeated for comparing between "Visuomotor task" and "View-only" trials. Here, significant time-electrode components will indicate interactions between the visuomotor task and auditory relevance.

4.4 RESULTS

4.4.1 *The role of auditory relevance on ERPs to environment sounds*

The environment sounds elicited a typical distraction potential in both groups (auditory irrelevant and auditory relevant). This distraction potential included a combined MMN/N1, a nP3 with an early and late peak and a RON. Figure 20 (top) shows the grand averaged waveforms of the elicited distraction potential for all electrodes, during the performance of the visuomotor tracking task. The mass univariate analysis reveals that this distraction potential was reduced for the group of participants for which the auditory modality was irrelevant (pink in Figure 20), relative to the group for which the auditory modality was relevant (green in Figure 20).

Interestingly, this attenuation was specific to one component of the distraction potential, namely the late nP3 over central electrodes. More specifically, the attenuation occurred in the time window of 395-492 ms in the electrodes: F3, FC5, FC1, T7, C3, CP1, CP5, P3, PO3, Fz, Cz, CPz, Pz, F4, FC6, FC2, C4, T8, CP2, CP6, PO4. The affected electrodes are marked white in the heat map in Figure 20 (bottom). Thus, the environment sounds are processed and elicit a distraction potential for both groups of participants. When the auditory modality is irrelevant the late nP3 of the distraction potential is attenuated, relative to the group for which the auditory modality is relevant.

4.4.2 *The interaction of auditory relevance and visuomotor demands*

Next, we investigate whether this selective difference in the late nP3 is affected by the cross-modal demands of performing a visuomotor control task. To do so, we derived the difference waveforms (Figure 21, left), which subtracted 'auditory irrelevant' ERPs from 'auditory relevant' ERPs, separately for when the participants performed the visuomotor task (blue line) and for the 'view-only' trials (orange line). A mass univariate analysis of these difference waves reveals that the effect of manipulating auditory relevance on distraction potentials does not differ between the trials for 'view only' and 'visuomotor

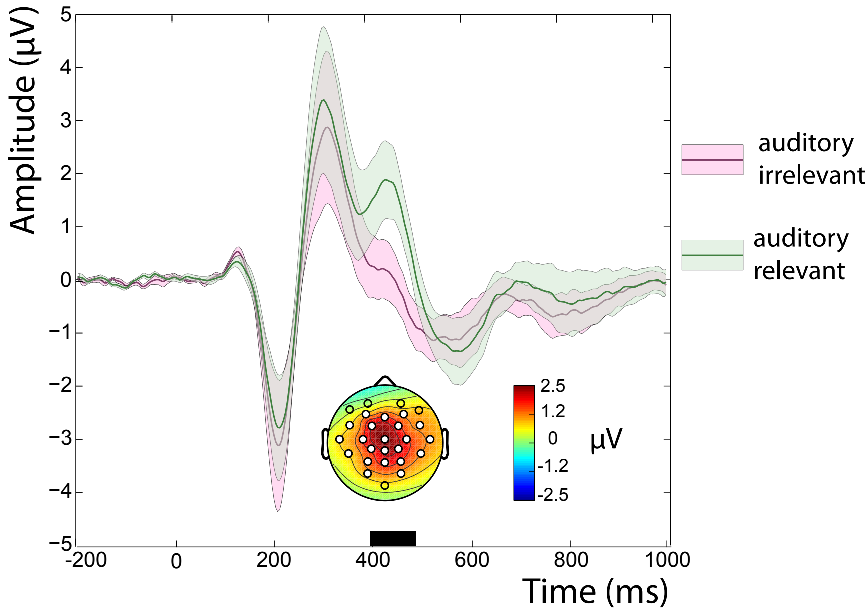

Figure 20: Grand averaged ERP to the environment sounds recorded during visuomotor tracking. For the 'auditory irrelevant' group, the ERP is depicted in pink, for the 'auditory relevant' in green. Shaded areas represented two standard deviations of the recorded electrodes. The black bar at the bottom marks the time-interval in which the ERPs differed significantly between the 'auditory relevant' and 'auditory irrelevant' group. The scalp topography of the difference between the conditions is provided for the significant time-interval as heat map. Electrodes at which the 'auditory relevant' and 'auditory irrelevant' group differed significantly from each other are marked white.

task', at any time-point or electrode.

Figure 21 (right) summarizes the results. To reiterate, there is a main effect of auditory relevance on late nP3 amplitudes ($F(1,23) = 16.10, p = 0.00, \eta_p = 0.01$) and a main effect of visuomotor task demands on late nP3 amplitudes ($F(1,23) = 6.38, p = 0.02, \eta_p = 0.12$). However, there is no significant interaction between auditory relevance and visuomotor task demands ($F(1,23) = 0.48, p = 0.49, \eta_p = 0.26$).

4.4.3 *Visuomotor performance and subjective workload*

ERP results suggest that task-irrelevant environment sounds were processed more when the auditory modality was task relevant. Here, we report that our manipulation of auditory relevance did not influence visuomotor performance nor self-reported mental

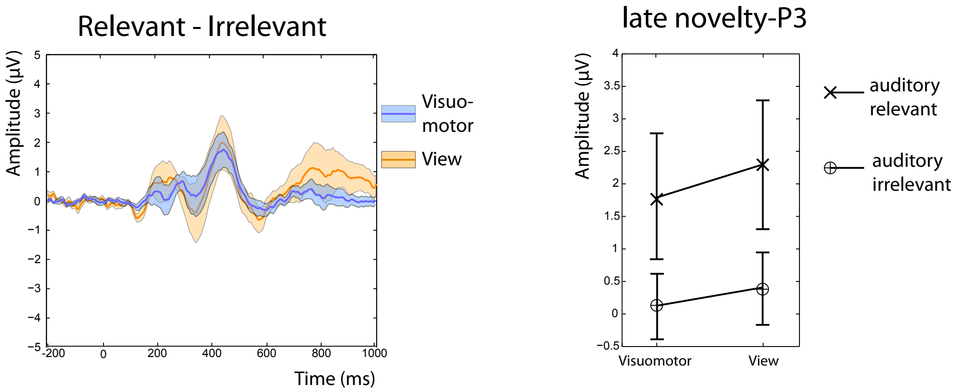

Figure 21: Left: Grand averaged difference wave of the environment ERPs between the 'auditory relevant' and 'auditory irrelevant' group. This difference wave was compared between the 'view only' (orange) and 'visuomotor task' (blue) trials. Shaded areas represented two standard deviations of the recorded electrodes. The effect of attention was not influenced by the visuomotor task. Right: Illustration of the interaction between the relevance of the auditory modality and the visuomotor task for the late nP3 peak. The vertical bars represent two standard deviations of measured late nP3 amplitudes.

workload scores (Figure 22). Visuomotor performance was calculated as the root-mean-

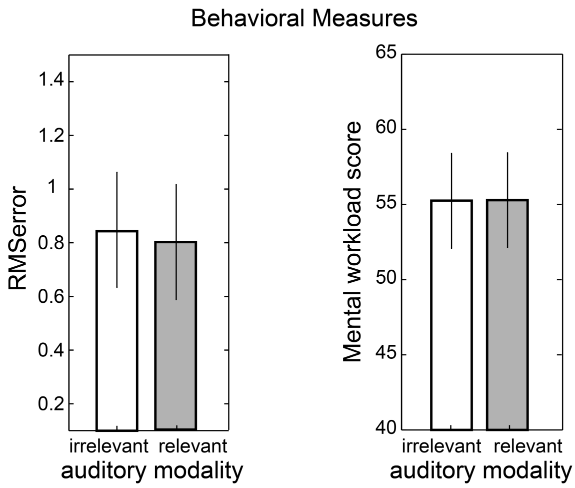

Figure 22: Left: Tracking error as normalized RMSerror for the group without (auditory irrelevant) and with (auditory relevant) the additional auditory target detection task. Right: Perceived and reported mental workload in the NASA-TLX questionnaire for the group without (auditory irrelevant) and with (auditory relevant) the additional auditory target detection task. Error bars represent the 95% confidence interval, based on the Cousineau-Morey method (Morey, 2008)

squared deviation (i.e., RMSerror) of the rotating line from the reference line, normalized to the roll disturbances of the task. A lower RMSerror indicates better performance. Visuomotor performance did not differ significantly between the two groups (t(23)=0.22, p=0.83, d=-0.06). Indeed, a JZS Bayes factor analysis suggested that tracking performance was unlikely to be different across these two conditions ($B_{10} = 0.29$). Thus, the additional auditory task did not impose a cross-modal demand on visuomotor performance.

Self-reported task demands (i.e., NASA-TLX scores) did not differ between the participant groups either (t(23)=0.01, p=0.99., d=-0.00). A JZS Bayes factor analysis suggested that self-reported task demands were unlikely to be different across these two conditions ($B_{10} = 0.29$). Thus, participants did not feel that it was more demanding to have to perform an additional auditory task in the current experiment.

It is worth noting that the auditory task was easy, given that the experimental objective was to simply introduce auditory relevance, rather than to study cross-modal conflicts. Participants who had to perform it generated high detection sensitivity (d': mean: 4.30, s.d.=0.70) and fast reaction times (0.61 s, s.d.= 0.07).

4.5 DISCUSSION

The current work investigated whether auditory irrelevance—namely, an absence of an obvious auditory task—would influence our brain's capacity for processing sounds in our auditory environment. We find that task relevance of the auditory modality selectively increases the late nP3 potential, which suggests that it increases the likelihood that our working memory will be updated for the occurrence of environment sounds with not obvious task relevance (Cycowicz and Friedman, 1998; Gaeta et al., 2003; Strobel et al., 2008). Earlier brain responses related to the detection and the orientation to environment sounds, i.e., N1 and early nP3 respectively, were not affected by auditory relevance. More importantly, this influence of auditory relevance on enhancing the late nP3 potential is independent of whether or not participants were required to perform a visuomotor task. Therefore, we conclude from our findings that auditory relevance enhances the likelihood that we update our working memory for environment sounds, regardless of the cross-modal demands of a concurrent visuomotor task. This supports our hypothesis that ID is not solely caused by high workload demands in the visual domain.

We structure the following discussion as follows. First, we discuss the influence of auditory irrelevance on our ability to process unexpected environment sounds and how this might differ from the influence of high visual workload. Next, we discuss how the independent role of auditory irrelevance from high cross-modal workload might relate to the concepts of arousal and passive fatigue. Finally, we conclude with an outlook on how our findings can be applied to mitigate the conditions that might give rise to ID.

In this work, we specifically analyzed the ERPs that were generated to environment sounds. The purpose of doing so was to ensure that we investigated our participants' general capacity to process auditory events that bore no task relevance. Such ERP waveforms have been termed distraction potentials because they indicate our available capacity to engage with events that have no immediate relevance (Escera and Corral, 2003). It is believed that underlying the distraction potential are neural components that are responsible for how we detect these unexpected events (i.e., MMN/N1), orient our attentional resources to these events (i.e., early nP3), update our working memory representation of the auditory environment with these events (i.e. late nP3), and re-orient the resources back to the task at hand (i.e. RON) (Escera and Corral, 2007, 2003; Horváth et al., 2008; Wetzel and Schröger, 2014). Currently, we find that auditory irrelevance selectively diminishes the late nP3 component and not the other components (i.e., N1/MMN, early nP3; see Figure 21). It should be pointed out that the ERP analysis that is employed in this study is data-driven. This means that we did not restrict our analyses to a priori ERP components.

If we assume that the chain of ERP components, which compose the distraction potential, reflects the consecutive steps that are necessary to process auditory events, the current results allow us to pinpoint the processing stage at which information could be lost when the auditory modality is task irrelevant. Namely, auditory irrelevance reduces our capacity to update our representation of our surroundings. It does not impair our ability to detect or to orient towards changes in the environment.

In contrast, the influence of high cross-modal demands can be more general or selective on the different stages of auditory processing, depending on the nature of the visual task. In our previous study, which is directly comparable to the current work, we demonstrated that the cross-modal demands of a concurrent visuomotor task are far less selective, in terms of its influence on distraction potentials (Scheer et al., 2016). Requiring participants to perform a visuomotor task does not diminish the early N1/MMN component of task-irrelevant environment sounds. However, it does diminish early nP3, late nP3, as well as the RON. The influence of cross-modal demands on auditory processing is likely to depend on whether the demands of the visual task is manipulated at either the perceptual or cognitive level (Lavie, 2005, 1995). Manipulations of high perceptual load in the visual task have been found to selectively decrease N1, whereby the argument would be that reduced auditory sensitivity is caused by the participants' inability to even detect the occurrence of auditory events in the first place (Kramer et al., 1995; Scannella et al., 2013; Singhal et al., 2002). On the other hand, manipulating the cognitive demands of the visual task—e.g., working memory load in a visual n-back task (SanMiguel et al., 2008) or the complexity an aviation decision task (Giraudet et al., 2015)—can selectively decrease later components such as P3 or RON.

Although there are different reasons for why and how high visual task demands might induce ID, it appears that auditory irrelevance has a more specific impact. It reduces our capacity to update our representation of the auditory environment, which is a plausible factor that could give rise to ID. It is important to point out that our current results suggest that auditory relevance increased the capacity for auditory processing at the late nP3 stage, independent of visuomotor demands. The current experiment did not create conditions that resulted in substantial conflict between the visuomotor and auditory task in a way that is apparent at the behavioral (i.e., visuomotor performance) or subjective (i.e., NASA-TLX workload) level (Figure 22). Therefore, we suggest that auditory relevance has an influence on modality-specific, instead of cross-modal, resources.

It continues to be debated whether attentional resources are shared between the modalities (i.e. cross-modal) or specific to them (i.e. modality-specific) (e.g. Keitel et al. (2013); Talsma et al. (2006); Wahn and König (2017). Experimental evidence exists for both assumptions. Numerous dual-task studies have shown that increased demands in a task, presented in one modality, often decreases performance levels in a concurrent task that is presented in another modality (Kramer et al., 1983; Sirevaag et al., 1989; Wickens et al., 1983). Nonetheless, the capacity of modality-specific resources can also be manipulated, similar to this study, without influencing the availability of resources in a separate modality. Keitel et al. (2013) employed a more direct approach than we have currently adopted, whereby concurrent streams of visual and auditory lexical items were presented and participants were explicitly instructed to attend either to the visual or auditory stream or both. Steady-state EEG/MEG responses indicated attending to either sensory stream of information could raise neural activity to that modality without diminishing activity in the unattended modality. In our study, we study the involuntary neural responses to environment sounds and find that one component (i.e., late nP3) can be enhanced by introducing modality relevance, in spite of the environment sounds continued irrelevance. Cross-modal visuomotor demands do not appear to diminish this effect.

It is likely that both cross-modal and modality-specific resources exist (c.f. Talsma et al. (2006)). For the phenomenon of ID, however, it might not be so straightforward as to attribute it entirely to a high workload demand for cross-modal resources. The increased capacity of modality-specific resources induced by modality relevance could, in itself, compensate for the risk of ID. The current study is limited in that we were unable to fully evaluate the cost of introducing auditory relevance. At first glance, it would appear that performance in the visuomotor task did not suffer as a consequence of introducing a simple auditory detection task. Neither was subjective workload increased. Nonetheless, it remains possible that introducing auditory relevance could detract from a general ability to respond to the visual environment, such as we have currently contrived for the auditory environment. One way of studying this would be to introduce comparable elements in the visual domain that are task irrelevant but, similar to environment sounds, elicit distraction potentials. The current findings have at least two important implications for human factor applications. To begin, decreased late nP3 could be used to index the risk of ID. This means that the operational scenarios that carry the risk of ID could be evaluated without relying on the observation of behavioral misses, which occur rarely if at all. Task irrelevant environment sounds can be embedded in many operational scenarios without compromising their integrity. Future research in signal processing and state classification could also be motivated to perform this assessment in real-time, instead of the off-line analysis that was performed here. Recent progress in the design of classification algorithms for ERPs is promising and shows that a classification of the state of the human operator is possible even with single trials (Blankertz et al., 2011;

Freeman et al., 1999; Wilson and Russell, 2003). For example, mental workload can be classified with an accuracy of more than 70% after only three presentations of the stimulus of interest, using ERP measures (Brouwer et al., 2012). More promising than the risk evaluation of ID is the potential prevention of its occurrence. Our findings show that unexpected auditory information generates larger late nP3 responses when the auditory modality contains a simple task that neither interferes with visuomotor control nor increases perceived workload. Requiring pilots to perform simple and frequent tasks in the auditory modality could heighten their awareness of the auditory environment, even in situations that pose high visual demands. This could prevent the occurrence of ID to critical auditory warnings (e.g., Dehais et al. (2014)).

To conclude, the current findings suggest that irrelevance of the auditory modality has a general effect of reducing late nP3 responses to environment sounds. We believe that this is a concomitant factor to the occurrence of ID in the real world, given the rare occurrence of auditory warnings and, hence, a default perception of the auditory modality as being task irrelevant. Auditory irrelevance and its impact on our reduced ability to update our representation of the auditory environment is an independent factor that does not interact with visuomotor demands.

5 APPENDIX

5.1 AUDITORY DISTRACTION IS DECREASED BY THE FAMILIARITY OF THE DISTRACTOR SOUND

5.1.1 *Introduction*

An unexpected and familiar sound in our auditory environment, for example a barking dog, can involuntarily attract our attentional resources. This is necessary in order to become aware of changes in our environment, which might affect our well-being. This phenomenon, which is also referred to as distraction, represents the involuntary part of the attention control system (see, Section 1.3). But does an unexpected auditory event need to be familiar in order to evoke a strong distraction? The current ERP-study investigates the influence of the familiarity of environment sounds, on their involuntary processing as well as on their interaction with a concurrently performed task.

In Chapter 2, we have compared two different types of distractor stimuli that are typically used to study auditory distraction. There, we could show that rare environment sounds, such as dog barks or human laughter, consume substantially more attentional resources than rare pure tones. Furthermore, only the environment sounds were shown to compete for attentional resources with a, concurrently performed, visuomotor control task. Based on these results alone it was, however, unclear what caused this difference in processing. Predictive coding theory (Friston, 2010), states that the amount of attentional resources that are attracted by an event critically depends on our expectations, concerning our auditory environment. These expectations are generated within the predictive model of the environment (see, Schröger et al. (2015b,a); Bendixen et al. (2012); Baldeweg (2006) and Section 1.3). Both the short-term context and long-term memory content are assumed to be represented in this predictive model (Schröger et al., 2015a).

The environment sounds, in Chapter 2, represented familiar objects in the long-term memory, such as dogs and laughing humans. Thus, it is plausible that this was the reason for the preferential processing of the environment sounds, relative to the pure tones. Indeed, it has been shown that familiar and personal meaningful sounds, such as the own name (e.g. Moray (1959); Berlad and Pratt (1995)), or a familiar voice (Holeckova et al., 2006) can result in preferential processing, relative to another persons name or an unfamiliar voice. Thus, it is plausible that especially familiar sounds are distracting for us.

In the current study, I investigate whether, indeed, the familiarity of an unexpected event increases the likelihood for its processing and thus could explain our results in Chapter 2.

In order to do so, I employed a modified novelty oddball detection task (see, Figure 5, left 2). In this task, participants were required to detect the rare pure tones that were intermixed with frequent standard tones. Furthermore, rare environment sounds were played, which were either familiar or unfamiliar sounds. The familiar and unfamiliar sounds were matched for their physical characteristics, such as onset loudness, overall loudness and frequency bandwidth. In order to find out whether the familiarity of an environment sound would enhance its processing, I compared the brain potentials (i.e. the ERPs) that were elicited by the familiar and the unfamiliar sounds.

Besides the involuntary attentional processing of the environment sounds, I was also interested in their interaction with a concurrently performed task. For this reason, in half of the trials my participants were involved in a visuomotor control task, while in the other half of the trials, they were asked to watch a pre-recording of the same task. Again, the brain potential that were elicited by familiar and unfamiliar environment sounds were compared between both types of trials.

If the familiarity of the environment sounds would be the reason for the preferential processing of the environment sounds and their interaction with the visuomotor control task, the ERP amplitudes that are elicited by the familiar sounds should be larger than those that are elicited by the unfamiliar sounds. In Chapter 2 the enhanced processing of the environment sounds was mostly reflected in novelty-P3 and RON, thus especially those subcomponents should be enhanced for the familiar, relative to the unfamiliar sounds. Furthermore, these ERP component should be decreased during the trials in which the participants were involved in the visuomotor control task for those ERPs that were elicited by the familiar sounds. The ERPs that were elicited by the unfamiliar sounds should not, or to a lesser degree, be influenced by the demand to perform a visuomotor control task.

5.1.2 *Methods*

Participants

I tested 24 right-handed volunteers (11 women, mean age=24.9 years, s.d.=3.21). All participants reported normal or corrected-to-normal vision, no hearing impairment and no history of neurological diseases. The experimental procedure was approved by the MPG Ethics Council and all participants gave written informed consent.

Stimuli and apparatus

The experiment was set up in a dimly-lit, low noise environment. It consisted of a primary visuomotor task and secondary auditory oddball task. The visuomotor control task was presented via a central display (1027 x 581 mm, resolution 1920 x 1080 px), approximately 130 cm away from the seated participants. Auditory stimuli were presented to both ears via headphones (MDR-CD380, Sony), that where driven by a soundcard (sampling frequency: 96 kHz; DELTA1010LT, M-Audio). A secondary heads-down display informed the participants of their most recent control performance and the current experimental status. Data collection was performed, using customized software, written in Matlab Simulink. The software version of the NASA-TLX questionnaire (Hart and Staveland, 1988) was presented on a separate notebook. For the visuomotor control task, a black cross (size: 1.5 cm) and a black circle (diameter: 11.5 cm) were presented on a grey background. The black cross was moving up and down, within the circle, as shown in Figure 23. A right-handed sidestick (Thrustmaster HOTAS Warthog, Guillemot, Montreal, Canada) was used as input device. For the auditory oddball task, participants were probed with stimuli with a random inter-stimulus interval (mean=1.20 s, s.d.=62 ms). Infrequently (prob. of presentation: p=0.1) presented target beep tones were intermixed with environment sounds (p=0.1) and frequent standards (p=0.8). Two easily

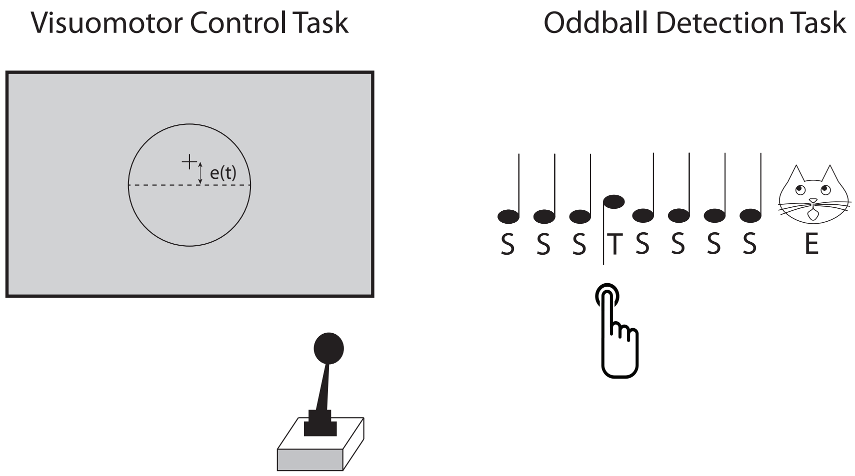

Figure 23: Left: Visuomotor control task. Participants were asked to compensate for the displacement e(t) of the cross, which was disturbed by random vertical motion. Right: Oddball detection task. Participants were asked to react to the rare target tones (T) with a button press. These target tones, as well as rare familiar and unfamiliar environment sounds (E) were intermixed in a series of frequent standard tones (S)

discriminable beep-tones were used (i.e., 300 and 700 Hz) and their probability (p=0.1 and p=0.8) was counter-balanced across participants. 128 complex sounds were used for the environment sounds. Of these environment sounds, 64 were familiar sounds and 64 unfamiliar sounds. The familiar sounds were selected from the NESSTI Database (Hocking et al., 2013) and belonged to one of four categories (animal, environment, human, man-made). From these 64 familiar sounds, 64 unfamiliar sounds were generated with the same overall intensity, spectral variation and temporal complexity as the familiar sounds. To generate the unfamiliar sounds, always two familiar sounds were morphed to generate two new unfamiliar sounds. In order to do so, the familiar sounds were first paired up in a way that made sure that both sounds originated from a different category (animal, environment, human, man-made). An example for such a pairing would be the sound of a cat (animal) and human laughter (human). Afterwards, both sounds were transformed in the frequency domain, using a fast fourier transformation. Like this, I could extract their magnitude and phase information. This magnitude and phase information was subsequently swapped between the two sounds to create two new and unfamiliar sounds. In the given example, the phase information of the cat was combined with the magnitude of the human laughter and vice versa. By transforming both back into the time domain, I obtained two unfamiliar complex sounds with the same phase magnitude content as the familiar sounds. Both, familiar and unfamiliar sounds, were normalized for intensity, by adjusting the root-mean-square intensity. To avoid clicking and ensure an equal sound onset, a trapezoid convolution was performed on all sounds. Both types of environment sounds were presented in quasi-random order without replacement and each sound was played approximately 5.54 times per participant. Environment sounds, as well as standards and target tones, had a duration of 500 ms and a mean intensity of 60 dB SPL (s.d.=0.31 dB). The environment sounds were always preceded by at least one standard tone. Participants were asked to press a button with their left thump, whenever they encountered the occurrence of a target tone.

Primary and secondary task

Participants performed a visuomotor control task in which they were required to continuously counteract the quasi-random vertical motion of the controlled cross and keep it as best as possible in the center of the stationary circle (see, Figure 23). A secondary oddball task was presented throughout the experiment and my participants were instructed to respond to the target tones as fast and accurate as possible and disregard the environment sounds. In half of the trials my participants were involved in the described visuomotor control task. In the other half of the trials they passively watched the same visualization, which was prerecorded before the experiment.

Design and procedure

The experiment consisted of two experimental sessions that were conducted on separate days. Each of these sessions consisted of four experimental blocks. Each block consisted of four trials, two trials in which participants were involved in the visuomotor control task and two in which they were not involved in the control task. Each trial had a duration of 4 min 26 seconds interleaved with 20 seconds of rest. A run-in time of 10 s was excluded for the statistical analysis, from every trial. During EEG preparation, participants were trained on the visuomotor control task for at least one trial. Only the visuomotor control task was trained. The oddball task started with the start of the experiment, after the training. Over the whole course of the experiment, after each trial, participants were presented with their visuomotor control performance to keep them motivated.

EEG signal processing

The EEG was recorded with 26 active g.tec Ag/AgCl electrodes (g.LADYbird, g.tec), mounted in an elastic cap (g.GAMMAcap, g.tec). The electrooculogram (EOG) was recorded from four additional electrodes: at the outer canthi of the left and right eye, and above and below the left eye. All recorded signals were re-referenced off-line to the linked mastoids. The ground electrode was placed at position FPz. The signals were amplified in the range between 0 and 2.4 kHz and digitized with a sampling rate of 256 Hz (g.USBamp, g.tec). Further processing and analysis of the ERP signal was performed with Matlab and the open source Matlab toolboxes EEGLAB (Delorme and Makeig, 2004) and ERPLAB (Lopez-Calderon and Luck, 2014). In the off-line preprocessing, the data was high pass filtered at 0.5 Hz and low pass filtered at 30 Hz. Second-order Butterworth filters were used for both filters. From the filtered data, epochs from -200 ms to 1000 ms, relative to the onset of the environment sounds, were extracted. Epochs that showed blink or eye movement characteristics, in any of the electrodes, were rejected. The remaining epochs were averaged and baseline corrected relative to the pre-stimulus interval.

Statistical analysis of the ERPs

For this appendix, only the ERPs from the environment sounds were analyzed for the manipulation of familiarity (familiar vs unfamiliar), for the manipulation of the visuomtor control task (control vs no control), and for their interaction. These comparisons were based on the mass univariate analysis. To perform the mass univariate analyses, measured brain potentials were compared between the relevant conditions at all time points (between 100 and 700 ms after the presentation of the auditory stimuli) and all measured electrodes (26 electrodes distributed over the scalp). Two-tailed t- tests were performed between the compared conditions to yield t-values for every time-point of each electrode. The false discovery rate (FDR) was controlled using the Benjamini, Hochberg procedure

(Benjamini and Hochberg, 1995) with a FDR level of 5%. This particular FDR procedure guarantees that the true FDR will approximate the nominal FDR level of 5%, regardless of the dependency structure of the multiple tests (a tutorial review of the mass univariate analysis is provided by Groppe et al. (2011)). This revealed time-electrode components that were significantly different during visuomotor control, relative to no control.

5.1.3 *Results*

Influence of the sound familiarity

In order to determine, whether the familiarity of the environment sounds had an influence on their ERP amplitudes, I compared their ERPs using mass univariate analysis. Figure 24 shows the results of this comparison. Early and late novelty-P3 were attenuated for the familiar sounds, relative to the unfamiliar sounds. The RON, in contrast, was enhanced for these familiar sounds.

Influence of the visuomotor control task

In order to replicate earlier findings that showed that the neccesity to perform a task decreases the processing of unexpected auditory events, I compared the ERPs that were elicited either in the trials with, or without, the visuomtor control task, by the environment sounds. Similar as in our previous studies the demand to perform a visuomotor control task, next to the oddball task, decreased a variety of ERP components (see Figure 25). In more detail during visuomotor control the inhibitory P1 was increased and MMN, early novelty-P3, late novelty-P3, RON were decreased.

Interaction between visuomotor control demands and sound familiarity

In the previous paragraphs, I established the influence of control demands and familiarity on the elicited ERPs. In order to determine whether both types of environment sounds would compete with the visuomotor control task for attentional resources, in a similar way, I analyzed the interaction between control demands and sound familiarity. For this reason, the difference wave between the ERPs that were elicited in trials without and

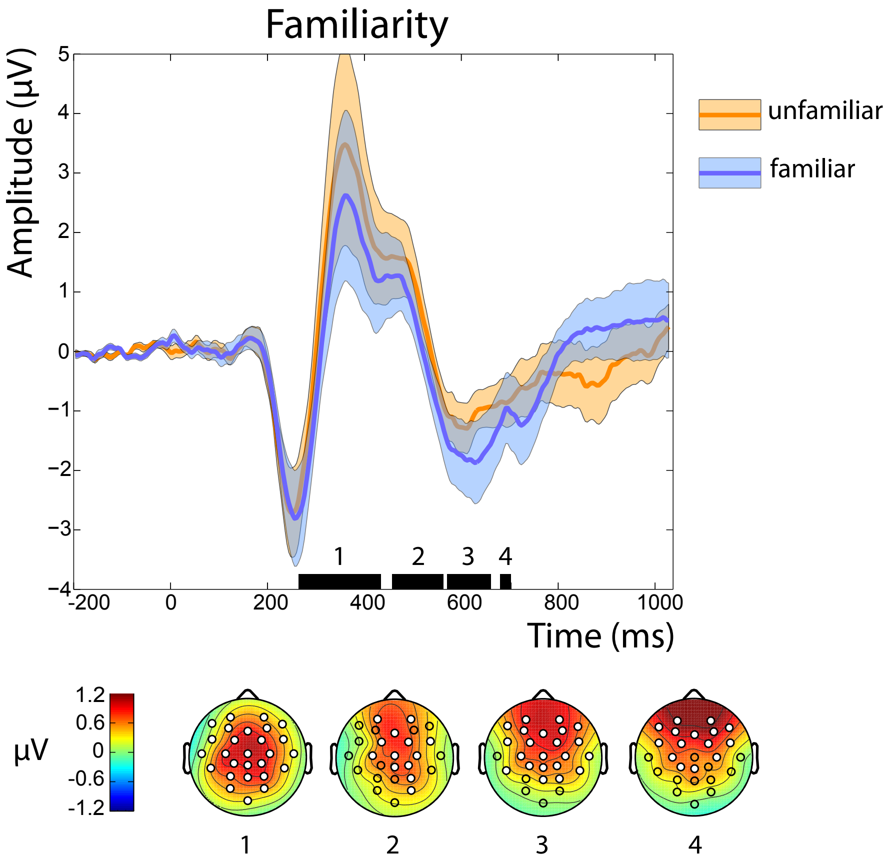

Figure 24: Top: Grand averaged ERP to the environment sounds (averaged over trials with and without the visuomotor control task) for the familiar (blue) and unfamiliar (orange) sounds. Shaded areas represented 2 standard deviations of the electrodes. The black bars at the bottom mark the time-ranges in which the ERPs differed significantly between conditions. Bottom: Scalp topographies for the found time-intervals. Scalp potentials are illustrated as heat maps and significant electrodes that differentiated between the conditions are marked white.

with control was calculated for the familiar and unfamiliar sounds. Subsequently the familiar and unfamiliar difference waves were compared. Figure 26 shows the result of these comparison. I did not find evidence to assume that ERPs from familiar and unfamiliar sounds are differently influenced by the demand to perform a visuomotor control task. Thus, although the familiarity of the environment sounds as well as the visuomotor control demands had an influence on the elicited ERPs, both of these factors did not interact.

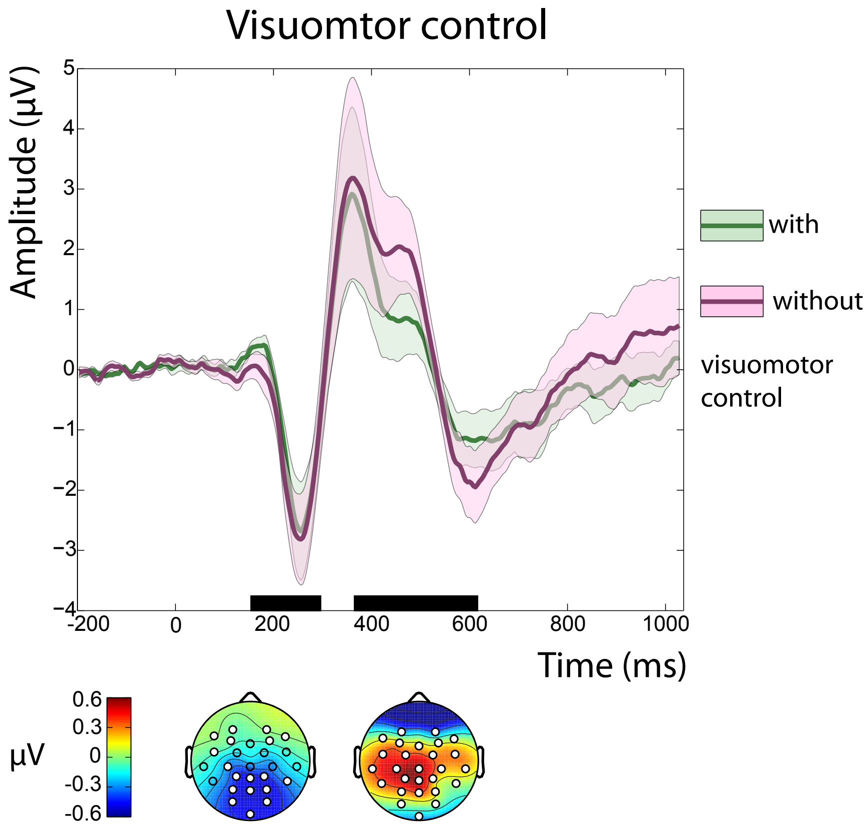

Figure 25: Top: Grand averaged ERP to the environment sounds (averaged over familiar and unfamiliar sounds) with visuomotor control (green) and without visuomotor control (pink). Shaded areas represented 2 standard deviations of the electrodes. The black bars at the bottom mark the time-ranges in which the ERPs differed significantly between conditions. Bottom: Scalp topographies for the found time-intervals. Scalp potentials are illustrated as heat maps and significant electrodes that that differentiated between the conditions are marked white.

Steering performance and behavioral distraction

In order to evaluate whether the familiarity of the environment sounds would have an influence on the visuomotor control performance, I evaluated whether the root-mean-squared error of my participants was different in the trials in which the environment sounds were familiar relative to such trials in which the environment sounds were unfamiliar. Furthermore, I evaluated whether the behavioral distraction, measured as the control effort, 1.2 s after the environment sound occurred (RMSinput), was influenced by the familiarity of the environment sounds.

For the statistical analysis, two-tailed, paired-samples t-tests were conducted between the trials with familiar and unfamiliar environment sounds. For these comparisons, an

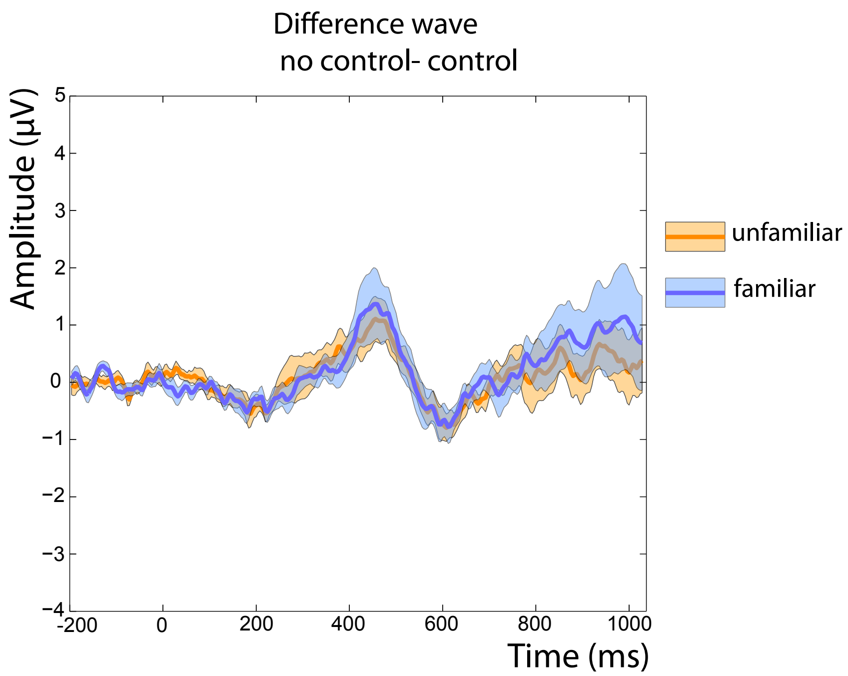

Figure 26: Grand averaged difference wave, between the trials with and without visuomotor control task, separately for the familiar (blue) and unfamiliar (orange) environment sounds. Shaded areas represented 2 standard deviations of the electrodes. The conditions were not significantly different at any time point.

alpha-level of 0.05 was adopted for significance testing. The Cohens d was calculated and is reported.

The familiarity of the environment sounds did not have a significant effect on the steering performance of my participants (t(23)=1.0, p=0.328, d=0.20). To quantify the likelihood that indeed the performance was not influenced by the familiarity of the environment sounds, I performed a JZS Bayes factor t-test. The Bayes Factor (BF_{10}) was 0.34. Thus, it is 3 times more likely that the null effect hypothesis is true than the alternative hypothesis. This data provides marginal evidence that the familiarity does not have an influence on the visuomotor control performance (Kass and Raftery, 1995).

Similar to the visuomotor control performance, the familiarity of the environment sounds did not have a significant influence on the behavioral distraction (t(23)=0.69, p=0.50, d=0.14). The Bayes Factor (BF_{10}) was 0.27. Thus, it is 3.74 times more likely that the null effect hypothesis is true than the alternative hypothesis. This data provides substantial evidence that the familiarity does not have an influence on the visuomotor control performance (Kass and Raftery, 1995).

My results suggest that the familiarity of the environment sounds did not have an influence on the visuomotor control task.

5.1.4 *Discussion and Conclusion*

The aim of the current study was to establish the role that the familiarity of an unexpected auditory event, such as a dog bark, plays in our involuntary processing of such events. Furthermore I wanted to find out whether the familiarity of the environment sounds was the reason why they were processed more than, equally probable, pure tones and compete for attentional resources with a concurrently performed task, as described in Chapter 2 of the current dissertation.

I showed that both types of the environment sounds resulted in a typical ERP wave, which is termed distraction potential (Escera and Corral, 2003; Wetzel and Schröger, 2014; Escera and Corral, 2007; Horváth et al., 2008). This distraction potential consisted of a MMN/N1, a novelty-P3 with a distinct early and late subcomponent and a RON.

The familiarity of the environment sounds, resulted in a significant attenuation of both phases of novelty-P3 as well as an enhancement of RON (see, Figure 24). Interestingly this did not have an effect on the interaction between familiarity and the demand to perform a visuomotor control task. Instead, the involuntary processing of both types of environment sounds was attenuated by the visuomotor control demands in a similar way (see, Figure 26).

The discussion of these findings is structured as follows. First, I will discuss the found difference in processing between the familiar and unfamiliar sounds, with respect to the three-staged model of distraction. Second, I will discuss my findings that suggest that the influence of familiarity, on auditory distraction, is independent from the demand to perform a visuomotor control task. Finally, I offer an alternative explanation for the found preferential processing of environment sounds, relative to pure tones, described in Chapter 2. Altogether, I believe that the current study contributes to our understanding of what types of sounds result in involuntary auditory distraction. This has implications for the design of warning sounds. Additionally, these results help to understand the processes that underlie auditory distraction and their interference with concurrently performed tasks.

The influence of familiarity on auditory distraction

In the current study, the familiar environment sounds elicited smaller early and late novelty-P3 amplitudes but a larger RON amplitude, relative to the unfamiliar environment sounds. Thus, we cannot conclude that familiarity is a necessary prerequisite for the preferential processing of environment sounds relative to pure tones, which was reported in Chapter 2. Instead some of its processing steps are enhanced, while others are attenuated.

The fact that for the familiar sounds the novelty-P3 is decreased in the current study, contradicts an earlier study, in which no influence of sound familiarity was reported for the novelty-P3 (Cycowicz and Friedman, 1998). However, the reason for this might be that, different than in the current study, Cycowicz and Friedman (1998) did not generate unfamiliar sounds but classified them to be familiar and unfamiliar, based on whether their participants could or could not name the environment sounds correctly, after the experiment. This could have resulted in some missclassification of the used sounds, simply because participants named sounds wrong, although they were familiar to them. This, in turn, might have diluted the effect of familiarity on novelty-P3. In the current study, I generated the unfamiliar sounds and thus I was sure that they were unfamiliar to my participants.

In the current study, early and late novelty-P3 show enhanced amplitudes for the unfamiliar sounds, relative to the familiar sounds. The early novelty-P3 was suggested to origin from the orientation of attentional resources to the unexpected event, while late novelty-P3 represents the updating of the working memory content with this event (Chapter 3 and Cycowicz and Friedman (1998); Gaeta et al. (2003); Strobel et al. (2008)). Based on this, I assume that unfamiliar sounds attract more attentional resources and are more likely to update the working memory than familiar sounds. Indeed, it has been suggested that unfamiliar visual and auditory events might be processed preferentially, because they trigger the generation of a working memory template, while such a template already exists for familiar events (Friedman et al., 2001; Henson, 2000). As the familiar sounds, for which already a memory template existed, required less attentional processing, more effort was taken to orient attentional resources away from the distraction, reflected in the increased RON amplitude relative to the unfamiliar sounds, possibly in order to use these resources for the processing of relevant information.

This suggests that if a sound should be designed to attract attention, like it is the case for warning sounds, or distractors in a scientific study, unfamiliar sounds should be preferred over familiar sounds. My results, furthermore, suggest that the familiarity of a sound, and thus the necessity for generating a new memory template, plays an important role in auditory distraction. Sounds, which do not already have a matching template are more distracting than sounds for which such a template already exists.

The influence of familiarity on the competition for attentional resources with the visuomotor control task

Although the familiarity influenced the amount of attentional resource that was oriented to the environment sounds, this seems to be independent of the visuomotor control task. Neither was the visuomotor control performance decreased in trials in which unfamiliar sounds were played, nor did they result in an increase in behavioural distraction, relative to the familiar sounds. Furthermore, I did not find evidence that the factor of familiarity and visuomotor control interact in their influence on the ERPs, which were elicited by the environment sounds.

This suggests that the increased consumption of attentional resources for the processing of the unfamiliar sounds, was not due to the fact that attentional resources were 'stolen away' from the visuomotor control task. In this sense, the familiarity is similar to the relevance of the auditory modality, which was discussed in Chapter 4. Both have an influence on the amount of attentional resources that is available for auditory processing but do not result in consumption of attentional resources that are shared between auditory and visual modality.

Why were environment sounds processed more than pure tones

My results did not explain why familiar environment sounds were processed more than pure tones in our study, reported in Chapter 2 of the current dissertation.

As described in Section 1.3, the involuntary processing of an unexpected auditory event depends on its comparison to the predictive model of our auditory environment. This predictive model represents the long-term memory content as well as the short-term context in which the event is presented in (Schröger et al., 2015a). Thus, besides the familiarity of a sounds, which can influence the auditory distraction due to their long-term representation, also the relation of a sounds to its local context can influence its processing. In Chapter 2, as well as in the current study, the environment sounds and the pure tones were presented in the context of frequent pure tones. Arguably, environmental sounds, which are a complex combination of multiple frequencies, are more dissimilar to this context than pure tones. This could have caused environmental sounds to have involuntarily recruited more attentional resources than the pure tones. If environment sounds recruit more attentional resources, which are shared between auditory and visual modality, it is also more likely that they compete for attentional resources with a concurrently performed task.

Indeed, an increase in the difference of an auditory event to its context was shown to have similar effects as we observed in Chapter 2 for the comparison between environment sounds and pure tones. Berti et al. (2004) parametrically increased the difference of the distracting auditory event from its context, by increasing the pitch difference between both. Like we reported for the comparison between environment sounds and pure tones in Chapter 2, such an increase in pitch difference resulted in an increase in novelty-P3 and RON as well as an increased competition for attentional resources with a concurrently performed auditory discrimination task.

For this reason, it is likely that the preferential processing of environment sounds, relative to pure tones, stems from their dissimilarity from their auditory context.

Summary and conclusion

In summary, I argue that unfamiliar environment sounds result in an increased orientation of attentional resources towards the environment sounds, relative to familiar sounds. This is possibly the case because attentional resources are required for the generation of a memory template for unfamiliar sounds, while such a template already exists for familiar sounds. Thus, if a sound should attract attention, as it is the case for warning sounds, or distractors in scientific studies, unfamiliar sounds should be preferred over familiar sounds. Especially for the former case (i.e. warning sounds) it is important to note that the increased attentional processing of the environment sounds was not at the expense of the, concurrently performed, visuomotor control task. This is relevant because a warning sound should warn the person without hampering his or her performance in the main task. It also suggests that unfamiliar sounds increase the availability of resources that are specific to the auditory modality, instead of 'steeling' resources away from the visually presented visuomotor control task.

However, my results contradict the hypothesis that environment sounds are processed more than pure tones because of their familiarity, which was stated in the beginning of this chapter. Based on predictive coding theory and earlier studies I suggest that the reason for the preferential processing of the environment sounds, relative to the pure tones, was that they differed more from the local auditory context.

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